Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 99 (2016) 137 – 146

Energy Procedia

10th International Renewable Energy Storage Conference, IRES 2016, 15-17 March 2016, Düsseldorf, Germany

Optimal Dispatch Scheduling of a Wind-Battery-System in German Power Market

Zhuang Cai[a,]*, Christian Bussar[a], Philipp Stöcker[a], Luiz Moraes Jr.[a], Dirk Magnor[a], Dirk Uwe Sauer[a]

[a]*PGS – Institute for Power Generation and Storage System, RWTH Aachen University, 52056 Aachen, Germany*

Abstract

Due to the principle of supply and demand, the real-time electricity price in the German spot market varies throughout a single day. Since wind power is non-controllable and partially unpredictable, it is difficult to schedule its power output. Suppliers lose profits by not taking full advantage of the price variation. Moreover, the forecast errors can represent a financial risk, in case of the provision of reserve energy. In this paper, an approach is presented where a battery energy storage system (BESS) is used to make wind power plants (WPPs) scheduled. First, the BESS is used to adjust the dispatch plan of wind power output, in order to exploit price variations beneficially in day-ahead and intraday markets. Second, the BESS is applied to address forecast errors during the real-time operation, in order to balance particularly the expensive forecast errors, which can endanger the stability of the power system. Deviations between forecast and real power output are characterized as expensive forecast errors, if the payment for the deviations is more than 50 €/MWh. In order to realize a multiuse of the battery, a genetic algorithm is employed to optimize the portion of power and energy capacity for the BESS, which participates in above-mentioned different energy market auctions. In contrast, for the daily operation strategy of the BESS, an hourly-discretized linear optimization algorithm is employed. The wind power forecasts for a pool of wind farms with an overall nominal power of 238 MW are generated with WEPROG‘s (WEPROG GmbH, Wetter & Energie PROGnosen, Böblingen, Germany, http://www.weprog.com/.) multi-scheme ensemble prediction system (MSEPS). In addition, the measured data of the wind farm pool were also available. Time-series data of electricity prices for the German/Austrian area are taken from EEX European Energy Exchange AG, Leipzig, Germany, https://www.eex.com/de/. and used partially for the optimization and verification. The results show that, by applying the proposed method, financial benefits are achieved for the wind farm and the cost caused by forecast errors can be decreased.

Peer-review under responsibility of EUROSOLAR - The European Association for Renewable Energy

* Corresponding author. Tel.: +49 241 80 49342; fax: +49 241 80 92203.
E-mail address: zcai@eonerc.rwth-aachen.de, pgs-batteries@eonerc.rwth-aachen.de

Peer-review under responsibility of EUROSOLAR - The European Association for Renewable Energy
doi:10.1016/j.egypro.2016.10.105

Keywords: dispatch scheduling; wind power forecast error; battery energy storage system; German energy market

1. Introduction

The renewable energy sector in Germany has been booming during the last decade. Especially the penetration of wind generators reached a level where almost 10 % of the yearly electricity demand can be covered by wind energy. For the marketing of wind power, it can be in principle divided into two different business models, namely fixed feed-in tariff model and direct marketing model. The fixed feed-in tariff model means that generated wind power is financially supported by a fixed tariff, which was originally an incentive to stimulate more investment into renewable energy industries. The direct marketing model means that generated wind energy is sold by private balance responsible parties (BRP) directly to the energy market, so that the wind energy is equally treated with the conventional energy at the same market price.

Direct marketing means higher expenses for independent power producers (IPPs), because the wind power has to be forecasted and the forecast errors will cause cost for balancing energy from TSOs. However, the dynamic electricity price in different energy markets gives also the incentive to develop an optimal trading strategy, which can benefit from the negative electricity prices and price variations. Considering the difficulty of direct marketing for wind power due to its fluctuation, battery storage energy systems can provide the flexibility to exploit the price variations and avoid the cost of balancing energy. Many storage technologies for example Li-ion batteries are constantly improving and becoming attractive for medium scale stationary energy storage applications. Due to the fast response time, there are no obstacles from a technical point of view preventing batteries from modifying the dispatch plan for WPPs immediately. The big challenge is currently still the cost which allows for the economic viability of the investment in BESS. Therefore, a variety of research focuses on business models allowing for economic operation of BESS considering different maturity levels and profit potentials.

In [3] the possible applications for BESS to support WPPs from technical and economical perspectives are summarized. Three main applications have been paid close attention to in this study: (1) deployment of primary control power, (2) balance of forecast errors and (3) improvement of direct marketing. The ability of BESS to fulfill the requirements to provide different types of control power has already been proven by some studies such as [4], [5] and [6] describe the possibility of BESS to provide primary control power for different country cases. [7] found that a wind farm with the capacity of 100 MW needs a BESS with the power and capacity of 34 MW/ 40 MWh for the maximum forecast errors of ±4 %. [8] and [9] discuss how to improve the direct marketing of wind power with the support of BESS as an optimization application to save costs and increase income.

Nomenclature

BESS	battery energy storage system
BRP	balance responsible parties
EEX	European Energy Exchange
IPPs	independent power producers
MSEPS	multi-scheme ensemble prediction system
TSO	transmission system operator
WPPs	wind power plants (WPPs)

2. Metheodology

2.1. German energy market

The European Energy Exchange (EEX) is a spot market for power. It operates day-ahead energy market and intraday energy market. The day-ahead market is organized by an auction process and closed on 12:00 p.m. one day before the physical delivery day. The intraday market is organized by continuous trading. The intraday market opens on 3:00 p.m. one day before the physical delivery day and closes up to 30 minutes before physical delivery. The control power is utilized in order to balance the forecast errors after the real-time operation. Furthermore, the day-after-market can be considered as the last chance to change the delivery plan. It closes on 4:00 p.m. one day after the physical delivery day. The TSOs are responsible for the energy balance between production and consumption. Based on the cost of control power, the TSOs will publish the balancing energy price each month for the previous month.

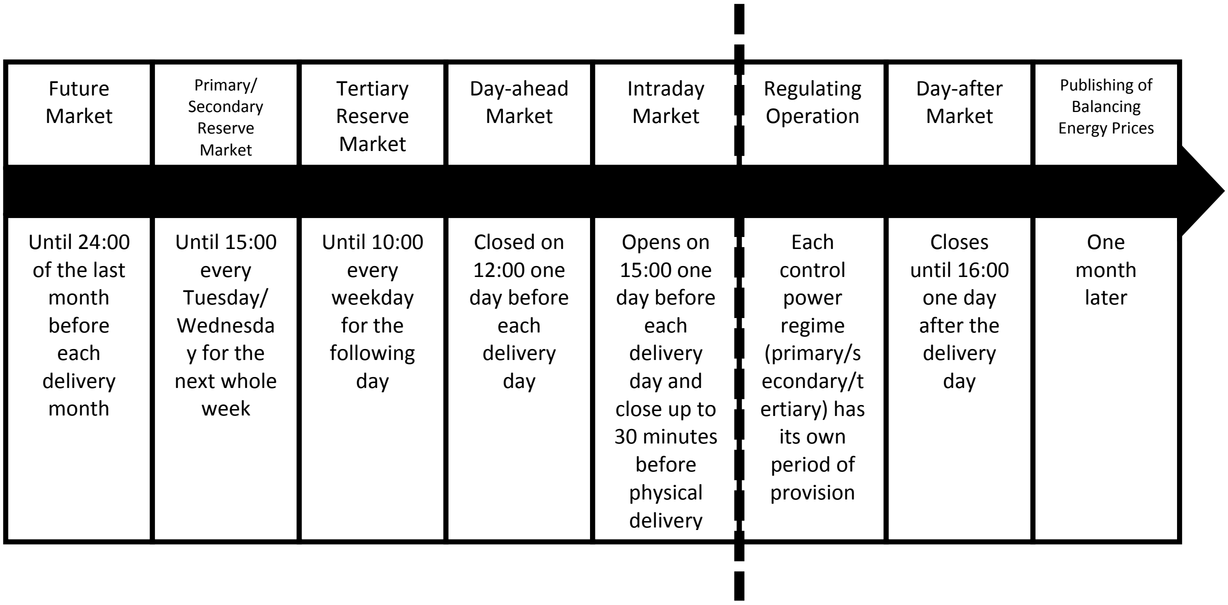

Fig. 1. The overview of marketing process

The overview of German marketing is illustrated in Fig. 1, in which the dotted line means the physical delivery. Considering that wind power forecasts are most accurate in the short-term, the active day-ahead and intraday markets are chosen in the following study to simulate a trading strategy for the chosen wind power pool. Our wind power pool has been chosen small enough to not have impact on any prices in the day-ahead or intraday market nor the balancing market. Meanwhile the cost of balancing energy due to the forecast errors is considered in the income calculation for the wind power pool.

2.2. Data

The wind power is being forecasted based on the weather data. The difference between the forecasted wind power and the physically measured wind power supply can be defined as the forecast error [9]. A forecast error with positive sign means that the wind power supply is overestimated by the forecast. In this situation, a certain volume of positive control power which can balance positive forecast errors is required. In contrast, a certain volume of negative control power must be used to balance negative forecast errors, which are caused by underestimation of wind power.

$$\Delta P = P_{FC} - P_{is} \tag{1}$$

As mentioned before, the wind power data from a pool of wind farms was supplied by a forecast provider in Germany for 2011-2012. The WPPs represent a total combined output of approximately 238 MW of installed capacity. A one-year time series of measured data with a production interval of one hour was also made available. Within the same time period the forecast data was generated with a forecast interval of 6 hours and a forecast horizon of 48 hours. It means that the wind power was forecasted each day beginning at 0:00, 06:00, 12:00 and 18:00 respectively and that each forecast had the same forecast horizon of 48 hours. According to the data structure of wind power forecast, a time series data for day-ahead forecast is determined by the forecast data from a 06 UTC run cycle that is available prior to gate closure of day-ahead market at 12 CET. The most recent and therefore potentially most reliable forecast data are required.

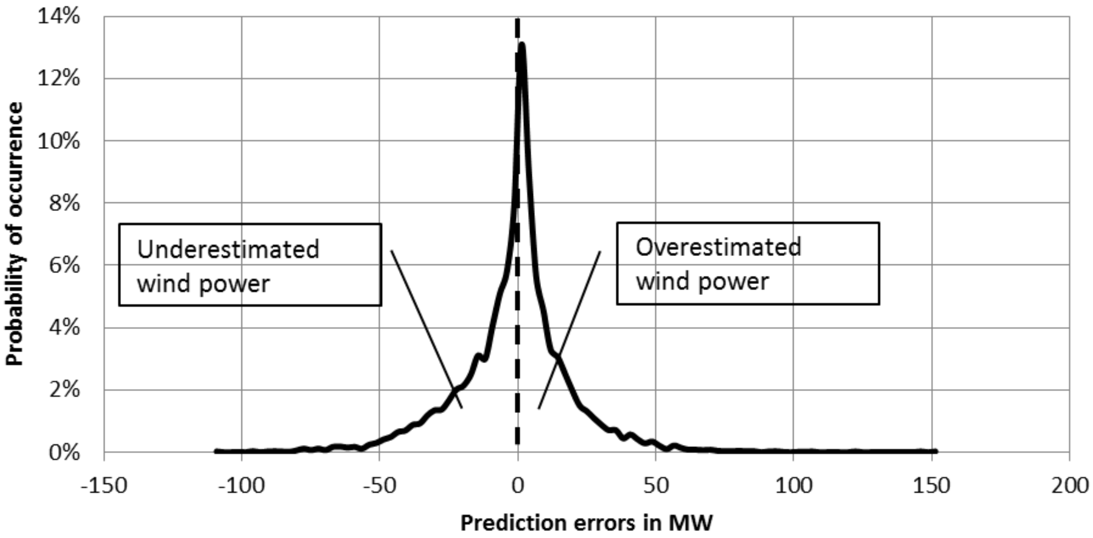

Fig. 2. Day-ahead forecast errors with the resolution of one hour for a wind farm during one year

In order to examine the distributions of forecast errors, Fig. 2 shows the occurrence probability of day-ahead forecast errors. The dataset covers one-hour forecast errors for a wind farm pool with the capacity of 238 MW during one year. The distribution has a pronounced peak, steep shoulder but also some extreme forecast errors, which can be dangerous for the power system stability. The dotted line, which means there are no errors, divides the distribution into two parts. The part at the left side of the dotted line means that the wind power was underestimated by the prediction. The part at the right side of the dotted line means that the wind power was overestimated by the prediction. It is obvious that the distribution is not symmetrical. However, most errors concentrate themselves around zero. The corresponding characteristic values can be found in Table 1.

Table 1. Evaluation of day-ahead forecast errors.

	Min (MW)	Max (MW)	Mean (MW)	Sum of positive errors (GWh)	Sum of negative errors (GWh)
Forecast error	-110	153	-1	57	-66

The time series data for the prices in day-ahead and intraday markets is available from the European Energy Exchange. The balancing energy prices are available from TSO 50Hertz Transmission [10]. The three different types of electricity prices are chosen from the same period with the wind power data and adjusted to form a resolution of 1 hour.

Fig. 3 shows a typical change for different market prices during one exemplary week. The day-ahead and intraday market prices have a similar regular variation tendency. Namely the values between 0:00 and 6:00 are small and two peak values exist in the morning and the evening. In contrast, the prices of balancing energy vary irregularly and even negative prices occur, which means IPPs have to pay to TSOs for the balancing energy even when they have overproduction due to forecast errors.

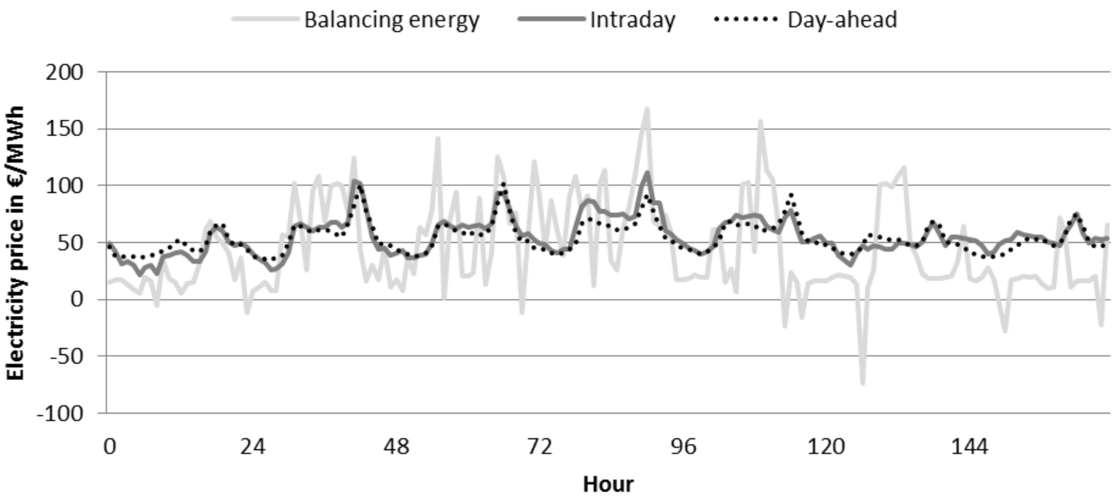

Fig. 3. The market price changes of three different types in a typical week

2.3. Optimization of the partition and the operation strategy for BESS

As mentioned before, the genetic algorithm is employed to optimize the partition of power and energy capacity of the BESS. Different parts of the BESS will supply energy and power capacity to different energy market products. The optimization of the power and capacity partition depends on the economic potential of different markets. For the daily operation strategy of the BESS, an hourly-discretized linear optimization algorithm is employed. The objective function is based on the fundamental optimization principles, which regulate the BESS to supply more energy during peak price periods and prevent unnecessary power delivery from the WPPs during low price periods. Meanwhile the WPPs can profit indirectly by avoiding the cost for balancing energy using a profitable operation strategy of BESS. The mathematical description of the objective function is represented as follows. Attention should be paid to the minus sign of balancing energy cost in equation (2), because the goal of the objective function is to maximize the profit of the wind-battery-system.

$$Max. \sum_{i=1}^{n} (p_i^D \cdot P_i^D) + \sum_{i=1}^{n} [p_i^I \cdot (B_{d_i}^I - B_{c_i}^I)] + \sum_{i=1}^{n} [-p_i^{BE} \cdot (P_i^{BE} - P_i^D)] \tag{2}$$

- n: number of time steps in the considered period
- D, I, BE: indices for Day-ahead, Intraday, Balancing Energy Market
- p_i: electricity price
- P_i: power output of the whole system (Power from WPPs and BESS)
- B_{d_i}, B_{c_i}: discharge and charge power of the BESS

with

$$P_i^D = P_{FC_i}^D + B_{d_i}^D - B_{c_i}^D \tag{3}$$

and

$$P_i^{BE} = P_{is_i}^{BE} + B_{d_i}^{BE} - B_{c_i}^{BE} \tag{4}$$

- P_{FC} : day-ahead forecast of wind power
- P_{is} : real physical power delivery

The initial partition of the BESS for each day in one week is generated randomly. Then the operation strategy of the BESS will be optimized day by day. In order to exploit the price variation every day, the state of charge of the BESS is the same for the beginning and the end of one day with a level of 50%. The power and capacity limit of the BESS is also considered in the simulation. After the optimization of the operation strategy for each day in one week, the fitness value which is represented in equation (2) will be calculated and evaluated. If the fitness value is not fulfilled by the requirements of termination conditions, a new generation with modified partitions of the BESS is generated by the evolution. The evolution will stop when the fitness value fulfils the criterions. The input data consist of technical parameters, technical limitations, electricity prices and wind power. This kind of optimization conception is represented in Fig. 4.

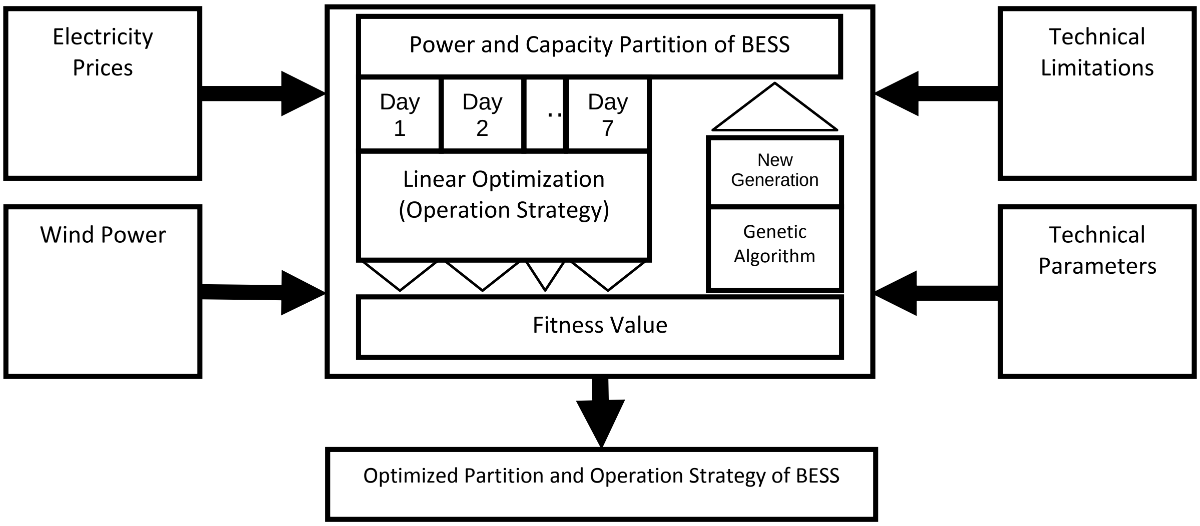

Fig. 4. The two-layer optimization structure

3. Results

3.1. Scenarios definition

In order to prove the ability of BESS, which can support profitably WPPs in different sectors of the energy markets, five scenarios of marketing wind power are defined as follows.

1) Marketing without BESS;
2) Marketing with BESS only in day-ahead market;
3) Marketing with BESS only in intraday market;
4) Marketing with BESS only in balancing forecast errors;
5) Marketing in a mixed trading strategy (the combination of 2, 3, 4).

In the simulations a BESS with a capacity of 100 MWh and a power of 50 MW is assumed. The genes in the chromosomes stand for the capacity and power partition of the BESS in each day. Thus, the number of genes depends on the number of simulation days and the trading strategy. For example, the number of genes in one chromosome is 7 times 3 if you have a simulation for one week with the mixed trading strategy. The number of chromosomes and the maximum number of generations are 100 and 300, respectively. In the next section, the optimized results from a one-week simulation are discussed.

3.2. Optimization results

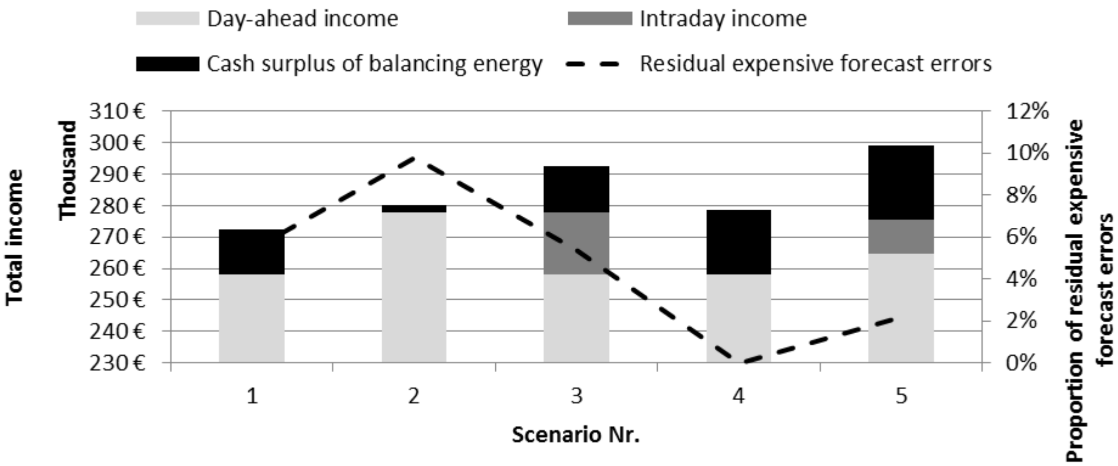

Fig. 5. Best fitness value of the five scenarios

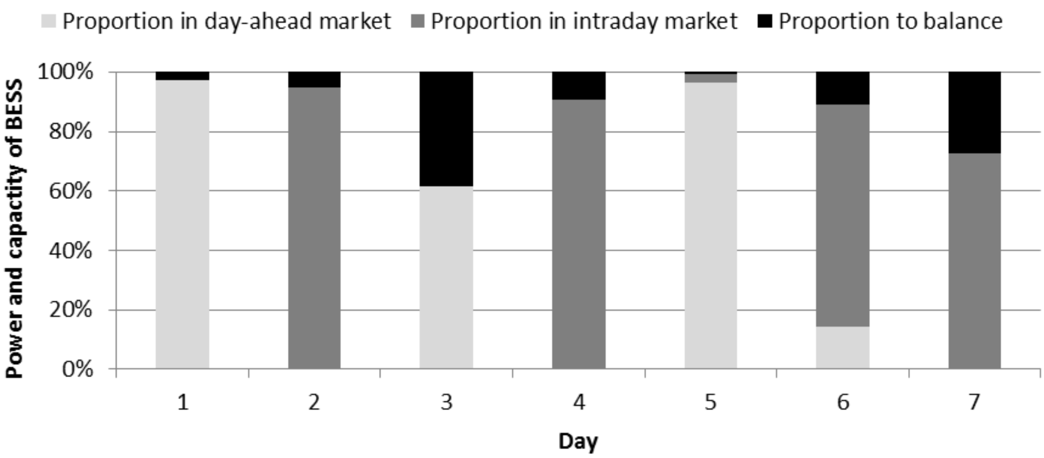

Fig. 6. The power and capacity partition for each day in the one-week simulation

In Fig. 5, the left vertical axis represents the total income for each scenario. The horizontal axis represents the number of scenarios. We show here the result for the best chromosome for each scenario. The histograms denote the income distribution for the WPPs for the different auctions in the energy market. The cash surplus for the balancing energy in this case is positive. It means the WPPs get so-called reward due to the forecast errors, which are beneficial to the power system. The income difference between the best case, namely scenario 5, and the worst case, namely scenario 1, is around 26 thousand Euros in one week. It can be explained by the fact that the BESS plays an important role in order to exploit the financial potential by participating in the different auctions of the energy market. The right vertical axis and the dotted line represent the proportion of residual expensive forecast errors to the aggregated volume of the total forecast errors. The expensive forecast errors can be defined as the errors, which cause the cash flow from WPPs to TSOs and have an absolute unit price for payment of balancing energy larger than 50 €/MWh. The optimization results indicate that the proportion of residual expensive forecast errors shows a relative low level in scenario 5 but not as good a level in scenario 4. This is because the BESS in scenario 4 is only responsible for balancing the forecast errors. As a whole, the mixed trading strategy can achieve a high income and a reduction of expensive forecast errors.

In Fig. 6, the gene's information form scenario 5 namely the power and capacity partitions of each day in the one-week simulation is represented. The partition for different auctions in the energy markets is different in each day. For example, the main portion of power and capacity of the BESS in the first and fifth day is committed on the day-ahead market and in the second and fourth day, the intraday market dominates the main portion of power and capacity of the BESS. However, the sixth day indicates a mixed distribution of different market auctions and it can be explained by the fact that the financial potentials in the three auctions are similar compared to each other.

4. Discussion

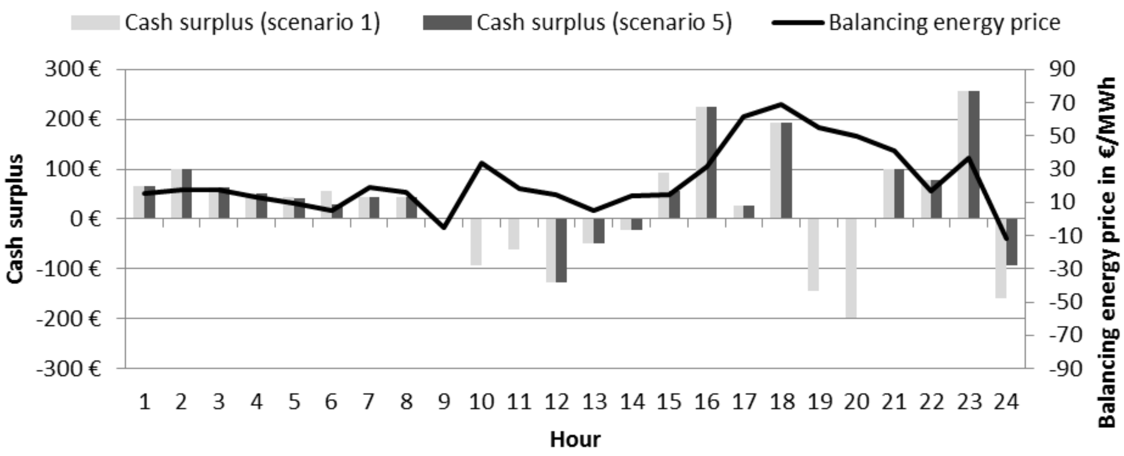

Fig. 7. Cash surplus regarding the balancing energy price in each hour

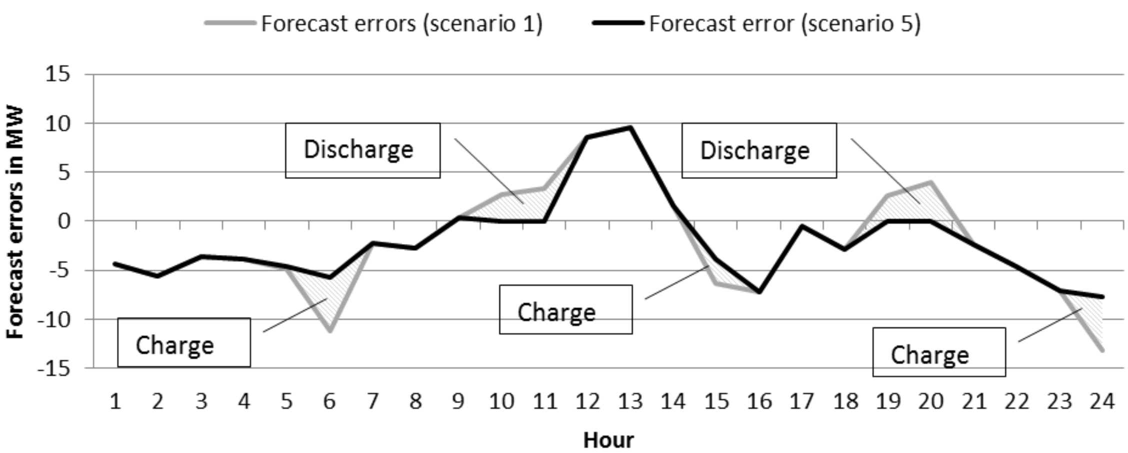

Fig. 8. Forecast errors of scenario 1 and 5 for one exemplary day

In order to prove the validity of the optimization results, the operation strategy of scenario 1 and scenario 5 of the BESS regarding the balancing energy price in the sixth day will be discussed in this section. In Fig. 7, the cash surplus in each hour regarding the balancing energy price is represented. The histograms correspond to the left vertical axis and the black line reflects the balancing energy price corresponding to the right vertical axis. In certain time periods, a negative cash surplus, which means that the cash flow from the WPPs to TSOs, is reduced or even totally compensated into zero by the operation of the BESS. However, the positive cash surpluses, which are also caused by forecast errors, are suppressed. These positive cash surpluses are not only beneficial to the WPPs as a kind of additional income, but also beneficial to the stability of the power system. Fig. 8 shows the forecast errors of scenario 1 and 5 in the same period. With the help of the BESS, the forecast errors are reduced from scenario 1 to scenario 5. The dashed areas in Fig. 8, which are marked with the labels “charge” or “discharge”, correspond to an operation of the BESS. The operation strategy results in a discharge of the BESS at relative high prices and in a charge of the BESS at relative low prices.

5. Conclusion

The dispatch plan of wind power is hard to control and the forecast errors are almost impossible to be avoided. However, the electricity price variations provide an economic incentive to change the dispatch plan according to the change of electricity prices during each day. Meanwhile the forecast errors have the potential risk to endanger the stability of the power system and enlarge the economic losses of the WPPs. Therefore the BESS is obviously an optional measure to support WPPs exploiting the variation of electricity prices and also saving balancing energy cost due to forecast errors. In this paper, the two-layer optimization structure is proposed to optimize the dimensional partition and the operation strategy of BESS. This method is applied to a one-week simulation for a wind-battery-system. The results indicate that the mixed trading strategy, which means the BESS is able to help WPPs participating in different parts of the energy market, can achieve a higher income than simple trading strategies. The economic potential of one week for the WPPs with a capacity of 238 MW has been found to be around 26 thousand Euros. Although this is by far not representative, it is worth nothing that the BESS system was capable to reduce the expensive forecast errors to a low level. We can therefore conclude that coupling WPPs with a BESS could help to establish a new trading opportunity and a new understanding of how renewable energy resource can participate also in the regulating market in the future.

The focus in this paper was to figure out the economic potential for the wind-battery-system and the methodology to realize a multiuse of a BESS for different energy market products. Because the investment of the BESS is not considered in the simulation, the study suggests that only existed BESS should at utmost help the WPPs to trade the energy. The effect of battery aging and battery cost will be considered in next step together with a longer period simulation in order to provide more representative optimization results. Because of the robustness and ability to extend the two-layer optimization structure, the simulation tool can be added with more elements such as solar generation or load consumption as next step in this study.

Acknowledgements

This work was based on the original data provided by WEPROG and we wish to acknowledge the collaborative efforts of WEPROG.

References

[1] WEPROG GmbH, Wetter & Energie PROGnosen, Böblingen, Germany, http://www.weprog.com/.
[2] European Energy Exchange AG, Leipzig, Germany, https://www.eex.com/de/.
[3] Wieland, M., and S. Gerhard, "Techno-ökonomische Bewertung von Lithium-Ionen Batteriespeichern an Windparks." Nachhaltige Energieversorgung und Integration von Speichern. Springer Fachmedien Wiesbaden, 2015. 187-192.
[4] BUNDESMINISTERIUM FÜR WIRTSCHAFT UND ENERGIE, ÖFFENTLICHKEITSARBEIT, Referat: Studie: Eignung von Speichertechnologien zum Erhalt der Systemsicherheit.
[5] Swierczynski, Maciej, et al., "Primary frequency regulation with Li-ion battery energy storage system: A case study for Denmark." ECCE Asia Downunder (ECCE Asia), 2013 IEEE. IEEE, 2013.
[6] SEBASTIAN GERHARD, FELIX HALFMANN, Entwurf einer Betriebsstrategie für Batteriespeicher zur Teilnahme am Primärregelleistungsmarkt, NEIS 2014, Hamburg, DOI: 10.13140/2.1.1534.8006.
[7] BREKKEN, TED K. A. ; YOKOCHI, Alex ; JOUANNE, Annette von ; YEN, Zuan Z. ; HAPKE, Hannes Max ; HALAMAY, Douglas A.: Optimal Energy Storage Sizing and Control for Wind Power Applications. In: IEEE Transactions on Sustainable Energy (2011).

[8] Zhuang Cai, et al., “Battery Storage System Size Optimization with Application of Statistical Distribution for Wind Power Forecast Error”, Proceedings of the 13th International Workshop on Large-Scale Integration of Wind Power into Power: Berlin, 11.11.-13.11.2014.

[9] Zhuang Cai, et al., “Application of Battery Storage for Compensation of Forecast Errors of Wind Power Generation in 2050” [J], Energy Procedia, Volume 73, June 2015, Pages 208–217.

[10] 50Hertz Transmission, berlin, Germany, http://www.50hertz.com/de.