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Dependency of Forecasting Accuracy for Balancing Power Supply by Weather-Dependent Renewable Energy Sources

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Abstract

The share of renewable energies in the national electricity generation systems is increasing worldwide, recently especially weather-dependent wind and solar power plays a substantial role. These energy sources are characterized by a fluctuating and imprecise predictable power generation, which increase the need of flexibilities within the remaining electricity systems (e.g., conventional power plants) to guarantee a high security of supply. Nowadays, these flexibilities are primarily provided by power plants based on fossil fuel energy. In future, these conventional power plants will increasingly displaced by an increasing renewable power supply. Thus, also weather-dependent renewable energy systems like windmills and PV systems need to contribute to the provision of balancing energy. Therefore, the aim of this paper is to analyse technical and energy economic conditions allowing weather-dependent renewable energy sources to contribute in markets for balancing energy and to estimate the scale of this contribution in a given energy system. As a basis, the day-ahead forecasting quality of the feed-in from wind park systems in Germany is analysed, to estimate the share of the wind power generation, which can be safely predicted for the following day. Based on probabilistic methods and the investigated results the theoretical potential of balancing energy delivered by wind mill systems can be calculated for a given supply area as well as for a defined degree of the security of electricity supply.

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Keywords: *wind energy, prognosis accuracy, balancing power*.

1. Introduction

The share of renewable energies is increasing worldwide; in 2014, more than 23 % of the global electricity production was produced by these sustainable energy sources [1]. This development is expected to continue in the future, because at least 144 countries around the world have implemented expansion targets for renewable energies [1]. Especially, the weather-dependent electricity generation from windmills and PV power plants play a substantial role within this renewable energy mix. However, their integration in electricity networks causes advanced system requirements due to their fluctuating and imprecise predictable power generation. Additionally, their feed-in prognosis and its reliability contribute to scheduling the generation of conventional power plants. These typically fossil fuel driven power plants guarantee a sufficient energy generation and a satisfactory provision of balancing energy to compensate forecast errors and high feed-in gradients of the renewable power supply. In future, with an increased share of wind and solar power supply, these conventional power plants will be increasingly displaced and thus weather-dependent renewable energy systems need to contribute to the secure provision of balancing energy. But so far, due to the current market regulations in Germany, these renewable energy systems do not make any contribution to the stability of the electric power system. The balancing power is mainly supplied by conventional power plants and pumped-storage hydro power stations. As a conclusion, even in the hours of high feed-in from wind and solar systems, conventional power plants must remain in the network in order to provide the necessary control power.

Against this background, the aim of the present paper is to analyse technical and energy economic conditions allowing weather-dependent renewable energy sources to contribute in markets for balancing energy. Subsequently, the scale of this contribution within a given energy system should be estimated. For an estimation of the capability of windmills and solar systems to provide balancing energy, the most limiting factor is their imprecise predictable power output. Therefore, the present paper gives an overview of the day-ahead forecasting quality of the feed-in from wind systems in Germany, to show which various constraints affect the forecast accuracy so far. Based on probabilistic methods, the share of the wind power generation, which can be predicted for the following day with a high probability, is estimated. Subsequently, the theoretical potential of balancing energy delivered by wind systems can be calculated for a given supply area as well as for a defined security of electricity supply. The results allow an evaluation of the impact of weather-dependent power supply on the electricity system balance, both for current and future time horizons.

The methodology explained above will be applied to wind energy systems and it is related to the German electricity network. Nevertheless, the methodology can be transferred to other electricity supply systems with, for example, different generation portfolios, other geographical conditions or varying levels of security of supply.

To provide positive control power, wind turbines have to operate on a throttled power level. This mode causes energetic and thus financial losses through the reduced power output, especially under consideration of forecasting inaccuracies and required reliabilities for balancing energy supply. Therefore, the present paper only assesses the potential of negative balancing energy provided by wind turbines.

2. 2. Methodology and Database

First, the forecasting accuracy of wind power has to be assessed to subsequently estimate the balancing energy potential by wind turbines. This is discussed below.

2.1. Assessment of Forecasting Accuracy

The day-ahead power forecasting is delivered by current regulations at 8 am for every quarter of an hour for the entire following day [2]. This yields to a forecast horizon from 16 to 40 h. This short-term forecasting is based on meteorological parameters predicted by numerical weather models, which are associated with the regionally distributed installed wind capacity and its measured feed-in. Deductive, the selection of the weather prediction model, and, thus, its regional and timely resolution, objective and adaptation to specific local conditions has a significant impact on the prognosis quality [3].

2.1.1. Mathematical Description

The forecast error X is the difference between the predicted value for the wind electricity generation to be feed into the grid Pr and the actual wind feed-in I ($X = Pr - I$). Positive forecast errors reflect an overestimation, negative an underestimation of the electricity supply from wind power. The prediction accuracy is characterized by the following parameters.

***Arithmetic mean** M.* This value represents the systematic error of the power prediction, which identifies an average over- or underestimation of the wind supply.

***Maximum and minimum forecast errors** X_{min}/X_{max}.* These parameters provide a first impression of the prediction accuracy. But they refer just to a singular event. Therefore, they have only limited significance [3].

***Root Mean Square Error** RMSE.* The *RMSE* indicates the scattering of the forecast error. Thus, this is an appropriate parameter for the assessment of power estimations. Due to the quadratic approach, larger errors are weighted with more significance and thus the economic impact on the electricity system is approximated in more detail [3].

Empirical probability distribution f. The distribution of the occurrence of forecast errors can be expressed by probability density functions. Discrete frequency distributions are converted in a continuous function using a kernel density estimation, e.g., with a Gaussian core [4]. The probability P that errors X only occur between the interval boundaries a and b can be calculated with a probability density function f according equation (1). In the same way, interval limits for defined probabilities can be determined. Thus, the previously described parameters can be specified for various confidence intervals:

$$P(X\epsilon[a,b]) = \int_a^b f(X)dX \qquad (1)$$

2.1.2. Scaling Factors for a Comparable Evaluation

A normalization of forecast errors allows a better comparability of the parameters described above for different boundary conditions. The applied scaling factors are listed below. Compared to previous studies (e.g., [5–7]) using mostly constant scaling factors, in the present paper variable time and yield dependent reference values have been selected.

***Installed capacity of the generating plants** P_{inst}.* This reference creates comparable conditions within different years and investigation area despite expansion of renewable energies.

***Predicted wind feed-in** Pr_{wind}.* The normalization to the predicted feed-in, being variable in time, enables a comparability of errors at different yield levels. Thus, the effect of higher absolute errors during periods with a high feed-in can be eliminated.

2.1.3. Time Dependence of Prediction Accuracy

The prediction accuracy of the wind power supply is evaluated with characteristics described above, but with a special focus on its time dependence. To evaluate the influence of the increasing forecast horizon, all data have been ranged according to their forecast horizon from 16 to 40 h and normalized to the predicted wind feed-in. Consequently, the results represent constraints, which significantly affect the prediction accuracy and identify development potential in meteorological, respectively, power forecasting models. Furthermore, the forecasting accuracy can be quantified in more detail, as a function of forecast horizon and predicted wind supply.

2.1.4. Reliability of the Prediction

Based on the cumulative probability distribution of the error, the "safe" predictable feed-in is determined for defined reliabilities. "Safe" in this respect describes power available with a certain (high) probability. Therefore, positive errors should be avoided, because by convention these errors cause an overestimation of the supply. The reliable forecast Pr_{safe} results from the expected feed-in I under a certain reliability S normalised to the current predicted feed-in Pr (equation (2)):

$$Pr_{\text{safe}}(S) = \frac{I(S)}{Pr} \qquad (2)$$

Fig. 1 shows on the basis of an exemplary distribution that negative errors occur with a probability $P(X\epsilon[-\infty, 0]) = P(X \leq 0) = 60\ \%$ and therefore positive error can be excluded with the same probability. A normalization to the predicted feed-in exemplify ranges on the abscissa $X \leq$ -100 % and $X \geq$ 100 %, in which errors are larger than the forecasted feed-in. With the objective of avoiding positive errors, above the limit $X = 100\,\%$ no share of the prognosis may be considered as safe. With a reliability $= P(X \leq 0) = 60\,\%$, an overestimation of predicted feed-in can be avoided and thus at least 100 % of the predicted feed-in can be considered as "safe" under this level of reliability (equation (3)):

$$P(X \leq 0) = 60\% \;\rightarrow\; X = \frac{Pr - I}{Pr} \leq 0 \;\rightarrow\; I \geq \mathrm{Pr} \;\rightarrow\; Pr_{\mathrm{safe}} = \frac{\geq Pr}{Pr} \geq 1 \quad (3)$$

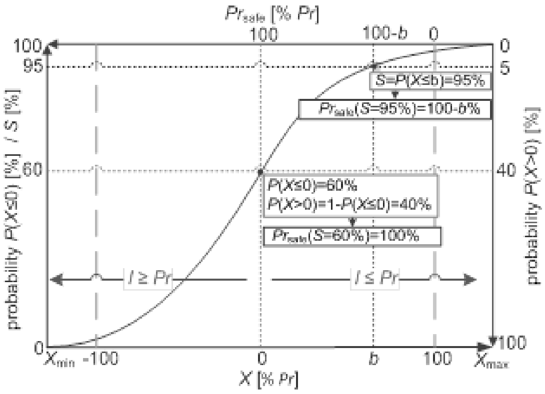

Figure 1: Methodology for estimating the safe predictable feed-in (X: forecast error; Pr_{safe}: safe prognosis; Pr: predicted wind feed-in; S: reliability).

To increase this reliability, S more errors – also negatives – has to be excluded. If $S = 95\,\%$, all errors $X \in [-\infty, b] = X \leq b$ are included in the forecast with $P = 95\,\%$ and the safe share of the forecast reduces dependent on the probability distribution of the error (equation (4)):

$$P(X \leq \mathrm{b}) = 95\% \;\rightarrow\; X \leq \mathrm{b} \;\rightarrow\; I \geq \mathrm{Pr}(1 - \mathrm{b}) \;\rightarrow\; Pr_{\mathrm{safe}} = \frac{\geq \mathrm{Pr}(1-b)}{Pr} = 1 - \mathrm{b} \quad (4)$$

This reliability of the forecasting accuracy represents similarly the required security of the balancing energy provision. Therefore, this analysed "safe" predictable part of the forecast is a precondition for the estimation of the negative balancing energy potential.

For the assessment of the forecasting accuracy day-ahead forecast errors of the wind power feed-in in Germany for every quarter of an hour from 2010 to 2015 have been analysed [2], [8], [9], [10]. The installed capacity, as one of the reference values, has been calculated using the Renewable Energy Law database [11].

2.2. Assessment of Balancing Energy Potential

To participate in the balancing power market, actors must provide offers with a defined product length and handling time. Depending on this submission date, respective forecast errors and its prognosis reliability have to be considered for determining the wind power supply and thus the control power potential. Consequently, balancing energy potential of wind turbines is mainly dependent from the following two factors.

- **Yield-dependent influences** like meteorological conditions, installed capacity of the generation portfolio, and regional distribution of wind turbines.
- **Market-regulating factors** like length of the control power products, submission date of the control power bid, and reliability of the balancing energy provision.

The German electricity system distinguishes primary, secondary and tertiary reserve, according to the engaging speed and the capacity of the control power [12]. Due to currently valid regulations for the German balancing energy market (e.g., weekly submissions, product lengths of at least 8 h, and a required reliability of 99 %), the market access for supply dependent renewable electricity generation from wind mills or PV systems is almost impossible [4], [13], [14]. Therefore, the control power potential is determined independent of the currently valid tender periods and product lengths of balancing energy offers and will be assessed according to the following factors:

- Dependency on different reliabilities of the forecast, respectively, balancing energy provision;
- dependency on different product length of balancing energy bids;
- dependency on regional resolution of wind parks; and
- dependency on size of wind parks.

The upper aspects represent market-regulating factors, the lower yield-dependent influences. The assessment follows the summarized methodology:

1. Determination of the feed-in by wind turbines on the basis of meteorological data [15] and regional distributed installed capacity [11]. The feed-in has been calculated for different regions in Germany, and various sized wind parks within the years 2012 to 2014.
2. Adjustment of (1) concerning the date of submission of the control power bid through consideration of the forecasting inaccuracy with particular reliabilities (within the following analysis only a day-ahead bidding is analysed; the day-ahead prognosis is integrated using results from the previous assessment (section 3)).
3. Adjustment of (2) concerning different product lengths of control power bids (within the following analysis product lengths of 1, 4, 12, and 24 h will be considered).

A comparison between calculated control power potential and need of control power in Germany shows to what extent wind power, despite fluctuating feed-in, can contribute to the system stability.

3. Assessment of Forecasting Accuracy

The development of the predictive quality of the German wide wind power supply in recent years is shown in Fig. 2. Maximum errors of the wind feed could be reduced despite increasing installed plant capacity. Comparably, forecasting accuracy of wind feed-in improves up to 18 % between 2010 and 2015. Also in the years 2007 to 2010, the accuracy increased [5]. Fig. 2 also shows that the mean of the forecast errors are predominantly positive. This means that the average wind supply is overestimated, which increases the need of positive balancing energy demand within the system.

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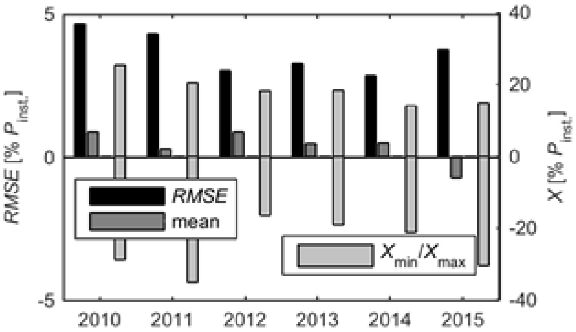

Figure 2: *RMSE*, arithmetic mean and maximum values of the forecast errors of wind power supply in Germany (X: forecast error; Pr_{safe}: safe prognosis; P_{inst}: installed wind capacity).

3.1. Time Dependence on Forecast Horizon

Fig. 3 shows the *RMSE* of the wind forecast errors, normalized to the predicted wind power, as a function of the forecast horizon. As expected, the quality decreases with increasing time horizon. The average forecast errors rise significantly in the range between 6 to 10 o'clock. From a forecast horizon of 26 h the forecast accuracy remains almost constant. Between different times of the day, the average forecasting quality differs up to 25 %.

Additionally, Fig. 3 shows the improvement of the prognosis accuracy in recent years. This reflects the development of the predictive quality shown in Fig. 2.

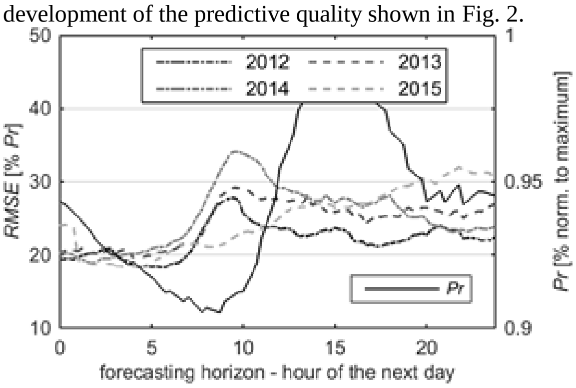

Figure 3: *RMSE* of the prognosis of the wind power feed-in and averaged predicted feed-in as a function of the forecast horizon (Pr: predicted wind feed-in).

To further differentiate whether the worse prognosis quality in the morning of the following day primary depends on the increasing forecast horizon or on feed-in volumes, the correlation between predicted power volume and forecasting accuracy has been investigated. Therefore, the data have been ranked in terms of their predicted feed-in volume and divided into three equal parts, summarizing small, medium and high forecast values [6]. The results shown in Table 1 indicate that the prediction accuracy significantly depends on the predicted feed-in volume. In details, it improves with higher predicted wind power volume; although absolute errors in the upper volume are almost three times higher and thus require a larger demand of the energy balance. Therefore, it can be concluded that the worse forecast quality in the morning hours of the following day can be predominantly justified by decreasing quality of the forecasting methods with increasing forecast horizon and by relatively small feed-in volumes during this time.

Table 1: Boundary limits and forecasting accuracy of categories with small, medium and high predicted feed-in values.

	small volumes	**medium volumes**	**high volumes**
boundary limits [% installed capacity P_{inst}]	0,7 – 6,8	6,8 – 15,6	15,6 – 92,7
***RMSE* [% predicted feed-in Pr]**	38,4	24,4	16,2

Summing up the analysis shows that the predictive accuracy of the day-ahead supply of wind energy systems significantly depends on the forecast horizon as well as on the amount of the predicted feed-in. Therefore, for the following analysis the forecasting accuracy will be considered in different levels of detail:

1. Constant over the entire forecasting horizon;
2. variable in the prediction horizon; and
3. variable in the prediction horizon and amount of predicted feed-in.

3.2. Reliable Day-Ahead Prediction

The assessment of "safe" predictable feed-in is a precondition for the estimation of the balancing energy potential. Applying distribution functions of forecast errors, the share of the day-ahead wind forecast, which can be predicted with certain reliability, can be calculated (section 2.1.4). This share has been calculated using forecast accuracies with different levels of detail (section 3.1). Table 2 shows these safe shares of predictable day-ahead wind feed-in, averaged over the investigation period (2012 to 2014), for reliabilities from 90 to 99.99 %. For instance, using forecast errors subdivided in their forecasting horizon and the particular predicted feed-in volume, up to 58 % higher shares can be reliable predicted for the following day. This tendency increases with increasing reliability of the forecast. As an example, Fig. 4 shows the respective "safe" prediction for reliabilities of 90.00 and 99.99 % differentiated in forecast horizon and in different predicted feed-in volumes. The decrease of the "safe" day-ahead prediction with increasing forecasting horizon and with smaller feed-in volumes is obvious.

For an assessment of the reliable day-ahead wind energy prediction, the application of forecast accuracies variable in forecast horizon and predicted feed-in volume enables to guarantee higher shares of wind energy supply. Consequently, for the following assessment of the balancing energy potential by wind turbines, the high level of detail of the forecast accuracy is maintained.

Table 2: Safe predictable day-ahead wind power feed-in [% of the predicted feed-in volume Pr] for forecast accuracies according method (a), (b), and (c) and different reliabilities.

reliability S [%]	(a) constant over the entire forecasting horizon [%]	(b) variable in prediction horizon [%]	(c) variable in horizon and amount of predicted feed-in [%]
90,00	63	63	69
95,00	52	52	61
99,00	33	35	46
99,90	19	20	30
99,99	10	10	23

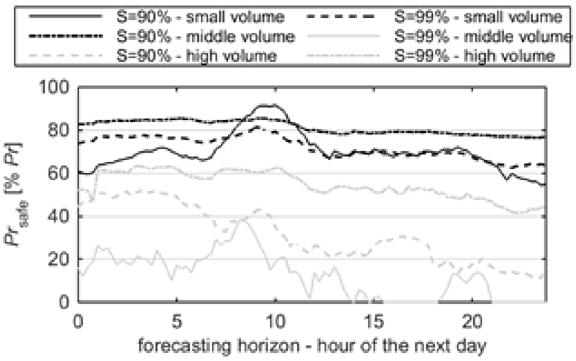

Figure 4: Safe predictable day-ahead wind power feed-in in % of the predicted feed-in. (Pr_{safe}: safe prognosis, Pr: predicted wind feed-in).

4. Assessment of Balancing Energy Potential

From a technical perspective, modern wind turbines can comply with the requirements of balancing markets [4], [16]. The prerequisite for this is a variable speed drive with simultaneous use of the pitch control concept. A model of the control concepts of a modern wind turbine shows that in a restricted operation a significant increase respectively decrease in power output can be realized within a maximum of 30 s [16], [17], and [18]. Irrespective of this technical operation scheme, meteorological conditions are a core requirement for the supply of wind-dependent balancing energy. Based on the methodology described in section 2.2, the balancing energy potential is estimated for the following dependencies.

4.1. Dependency on Different Reliabilities of the Prediction

Fig. 5 (left column in each section) shows the theoretical balancing energy potential (product length 4 h, normalized to the installed wind power) for a wind park pool with an installed capacity of 1 GW under average meteorological conditions (wind speed at 3.6 m/s in a height of 10 m) and without consideration of wind power forecast errors. The other columns represent the decrease of balancing energy potential under consideration of forecasting errors and their particular forecast, respectively, supply reliability between 90 and 99.99 %. The several sections reflect the different levels of detail to quantify the forecasting accuracy (section 3.2). With increasing level of reliability, decreasing shares of the wind power can be securely predicted and thus the control power potential decreases significantly. This tendency is more distinctive for forecast accuracies with a lower level of detail. Using forecast accuracies variable in time and predicted feed-in volume, the average balancing power potential at a required safety level of 99.99 % increases up to 67 % compared to constant forecast accuracy over the entire time of the day. Therefore, within the following assessments of balancing energy potentials the forecasting accuracy according to method (c) is applied.

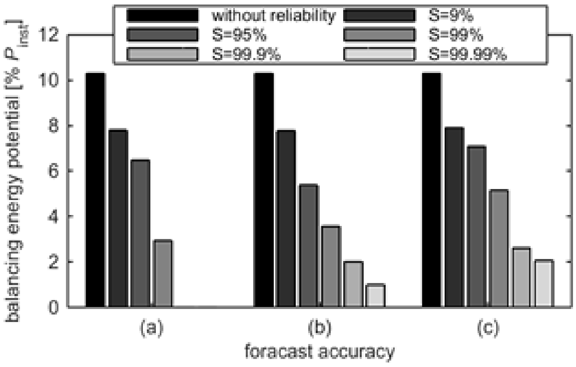

Figure 5: Balancing energy potential for different levels of detail of forecast accuracy and different reliabilities (P_{inst}: installed wind capacity).

4.2. Dependency on Different Product Length

Fig. 6 (left column in each section) shows the impact of different product length of balancing energy offers for the same wind park as in the previous investigation. The prediction accuracy of methodology (c) and a reliability of supply of 99.99 % is applied. Due to the fluctuating wind energy feed-in, the theoretical provided potential of balancing energy decreases significantly with increasing length of the product.

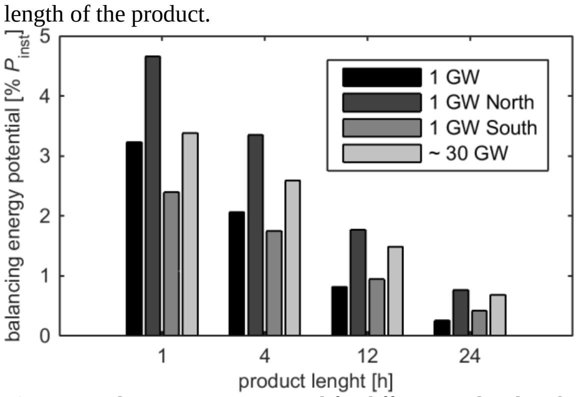

Figure 6: Balancing energy potential for different product length, regions, and sized wind parks (P_{inst}: installed wind capacity).

4.3. Dependency on Regional Resolution

In addition to market regulating factors, yield-dependent conditions influence the potential of balancing energy by wind turbines. Therefore, Fig. 6 (second and third column) shows the importance of sufficient meteorological conditions by comparing two further 1 GW wind parks. The values of these exemplary wind parks are an average of three wind parks located in the North, respectively, South of Germany. Compared to the South the North of Germany is characterized by higher and less fluctuating wind speeds. Deductive, the average wind park located in the North has an around 50 % higher potential of balancing energy compared to the wind park located in the Southern part of Germany.

4.4. Dependency on Size of Wind Parks

Furthermore, Fig. 6 represents the impact of regional equalization effects within wind supply. With increasing distance between wind measurement stations, the correlation between their particular wind speeds decrease [16]. This effect can be transferred to the superposition of short-term fluctuations in the wind generation of distant wind farms, particularly between wind parks in areas with different weather conditions. Additionally, increased forecast accuracy in expanded areas is directly linked to this effect. The described impact of regional equalization effects on the balancing energy potential is assessed by comparing the 1 GW wind park from the previous investigation (Section 4.1) (Fig. 6, left column) and the exemplary German wind turbine portfolio, with around 30 GW (Fig. 6, right column). This investigation shows exemplary that a vast regional distributed and a more powerful wind farm has an increased relative balancing energy potential of around 30 %.

5. Conclusion and Future Prospects

The future energy supply will be characterized by further increasing integration of weather-dependent energy sources. To guarantee an efficient and safe operation of these sustainable electricity systems, feed-in prognosis will continue to be an indispensable part of the daily energy management and trading.

Therefore, the present paper provides an overview of the current prediction accuracy of wind supply in Germany. In this context, significant dependencies of the forecast errors could be identified. Decreasing prediction accuracy with lower predicted feed-in volume and increasing forecast horizon is characteristic. The results on one hand identify factors of influence for a further development of meteorological, respectively, power forecasting models, and on the other hand enable a detailed quantification of the day-ahead forecast accuracy variable in time and feed-in volume. By means of probabilistic classifications of the forecast errors, the day-ahead predicted wind feed-in could be subdivided in a reliable and non-reliable prognosis. This safe predictable day-ahead supply increases with decreasing reliabilities of the forecast quality and is basis for the assessment of the theoretical balancing energy potential by wind turbines for the following day. This potential is influenced by market-regulating and yield-dependent factors. It increases with shorter product lengths of bids, improved forecast accuracy of wind power feed-in, respectively, short-term tendering periods, and lower reliability levels of balancing power supply. Furthermore, an increased potential can be offered by bundling regional distributed wind farms. The whole wind energy portfolio in Germany could provide a maximum system capacity of 1.5 GW under a required level of security of 99.99 % as an annual average. The averaged need of tertiary balancing energy in Germany between the years 2013 and 2015 was in a range of 2.5 GW [12]. Therefore, already today wind turbines could significantly contribute to the system stability. According to [19], the demand for balancing energy is expected to increase due to integration of higher shares of weather-dependent renewable energy systems. This increase counteracts with improving forecast accuracies through advancement of prognosis models, and the equalization of wind power feed-in through increased installation of offshore wind turbines [20]. Nevertheless, through a possible integration of wind turbines in the balancing energy market, the Must-Run base of conventional power plants in the system could be reduced. But for this economically and environmentally efficient use of wind turbines in the German active and balancing power market, the regulatory and market-economic conditions have to be adjusted. For the provision of control power by a regionally distributed wind parks, the capacity of the electrical network must be examined separately, in order to reduce additional network loads. Moreover, the control power potential of wind turbines could be increased through combinations with solar systems and storage opportunities. A temporal analysis of the need of control power and theoretical balancing energy potentials by renewables specifies the impact of weather-dependent renewable energy systems on active and control power supply system in temporal and spatial resolution.

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