Economics of control reserve provision by fluctuating renewable energy sources

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***Abstract*—The delivery of control reserve by fluctuating renewable energy sources (RES) generators will be important in an energy system with high RES penetration. This paper extends a previously introduced methodology to quantify the possible additional income of different pools of fluctuating RES generators in the negative secondary and tertiary control reserve market in Germany. The updated methodology allows concluding on the ideal market conditions by comparing different pool types and years. The development of the results over a long assessment period allows extrapolating the market value of the new market participants into the future. Results show a high dependency of the possible additional income on the overall market size and the market conditions and regulations.**

***Index Terms*—Reserve markets, Wind farms, Photovoltaic systems, Market value estimation, Econometric modelling**

I. Introduction & Problem Statement

In a future energy system, fluctuating renewable energy sources (RES) generators will have an increasing responsibility for providing ancillary services, such as frequency control. Bringing these units to the market requires changes of the regulations in a way that suits all market participants in a non-discriminatory way. Determining these changes mandates that the impact on the possible market participation be evaluated.

A. Conclusions from the literature

Previous studies have shown that providing frequency control reserves is possible with wind farms [1, 2] and with photovoltaic (PV) systems [3, 4]. This includes market based procured control reserve (CR) as well as even faster responding virtual inertia.

Different methodologies for assessing the economic impact are available that often quantify the possible income of new market participants with different technologies [5–8]. It was found that the market participants' behaviour is governed by their income opportunities rather than their costs, which excludes purely cost-bases approaches [9]. Hindcast modelling allows to reduce the impact of volatile prices with a high level of uncertainty [10]. The findings suggest that a purpose-built modelling approach with hindcasting techniques and welfare economics should be used.

B. Expected results from this work

This work aims on quantifying the economic benefits from wind farms and PV systems participating in the German market for negative secondary (SCR) and tertiary control reserve (TCR) markets as price takers. A methodology to calculate costs saving potentials for the power system is presented using a hindcasting model, based on [11]. Parameters, such as product specifications, have been varied in order to identify the impact on the income and the implications of market design adjustments.

II. The REBal model

The assessment is carried out in two steps by means of the REBal model presented in [11]. First, the size of control reserve bids from fluctuating RES is determined. Second, the possible income is calculated based on shifting high price bids in the merit-order list beyond the demanded volume. This methodology was extended for this study. The method applied is a hindcasting model that assesses the economic impact of fluctuating RES generators in the CR market from the supply and the demand side.

A. Bid creation for the market

1) Probabilistic forecasts for capacity bids

Bids submitted in the CR market require the specification of a volume, a capacity price and an energy price. The volume is the capacity that is reliably available for activation by the transmission system operator (TSO).

The first step of the REBal model is determining the reliable capacity of wind and solar power forecasts. According to [12] a reliability of 99.994% is required from the power forecasts. Probabilistic forecasts enable determining a capacity at a defined value of reliability (see e.g. [13]). The REBal model uses a kernel density estimator (KDE) with Gaussian kernels to calculate probabilistic forecasts for different levels of reliability. The KDE approach is based on the findings of Bowman and Azzalini [14].

A two-dimensional KDE allows the creation of a probabilistic day-ahead forecast for fluctuating RES, estimating the forecast uncertainty (i.e. forecast error) of a power forecast (i.e. day-ahead forecast). According to [14], equation (1) returns the probability density estimation function $\hat{f}_{DA}$ for the day-ahead (DA) forecast with Gaussian kernels and the bandwidth estimator h. P_f is the value pair of the forecast with $P_{f,1}$ to $P_{f,n}$ being the individual values. P_e is the value pair of the forecast error, with the values $P_{e,1}$ to $P_{e,n}$ for the value from 1 to n. h_f is the bandwidth of the forecast and h_e the bandwidth of the forecast errors.

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$$\hat{f}_{DA}(P_f,P_e)= \frac{1}{n}\sum_{i=1}^{n} \frac{e^{-\frac{1}{2}\left(\frac{P_f-P_{f,i}}{h_f}\right)^2}}{h_f\sqrt{2\pi}} \cdot \frac{e^{-\frac{1}{2}\left(\frac{P_e-P_{e,i}}{h_e}\right)^2}}{h_e\sqrt{2\pi}} \quad (1)$$

The intraday (ID) forecast additionally includes the forecast errors that have occurred before. This expands (1) and returns the following density estimation function for the intraday forecast $\hat{f}_{ID}$ in (2). P_{pe1} and P_{pe2} are the value pairs of two different pre-errors for the number of value pairs n. h_{pe1} and h_{pe2} are the corresponding bandwidths.

$$\hat{f}_{ID}\left(P_f,P_e, P_{pe,1},P_{pe,2}\right)=$$
$$\frac{1}{n}\sum_{i=1}^{n} \frac{e^{-\frac{1}{2}\left(\frac{P_f-P_{f,i}}{h_f}\right)^2}}{h_f\sqrt{2\pi}} \cdot \frac{e^{-\frac{1}{2}\left(\frac{P_e-P_{e,i}}{h_e}\right)^2}}{h_e\sqrt{2\pi}} \cdot \frac{e^{-\frac{1}{2}\left(\frac{P_{pe_1}-P_{pe_{1},i}}{h_{pe_1}}\right)^2}}{h_{pe_1}\sqrt{2\pi}} \cdot \frac{e^{-\frac{1}{2}\left(\frac{P_{pe_2}-P_{pe_{2},i}}{h_{pe_2}}\right)^2}}{h_{pe_2}\sqrt{2\pi}} \quad (2)$$

Based on the individual probability density functions $\hat{f}_{DA}(P_e)$ and $\hat{f}_{ID}(P_e)$ for each forecast value at the time step t the probabilistic forecast values P_{probFC} for a defined level of reliability are extracted, using a numerical search algorithm in the REBal model. This yields $P_{offer}(T)$ in every product period T over the values from 1 to x.

$$P_{offer}(T)= \min(P_{probFC,1},P_{probFC,2},\ldots, P_{probFC,x}) \quad (3)$$

2) Capacity prices

a) Opportunity cost driven bids

The regulatory framework, taking into account the opportunity cost based approach, determines the opportunity costs of fluctuating RES generators providing CR. The capacity price of the bid is the auctioning criterion in the CR markets, expressed in EUR/MW/h. The opportunity cost based capacity prices compare the income $I_{CRMarket}(t)$ of fluctuating RES at the time t with CR market participation with the income $I_{noMarket}(t)$ without CR market participation. The capacity price for the product period T therefore is:

$$CP_{op}(T)=\frac{I_{noMarket}(T)-I_{CRMarket}(T)}{\sum P_{offer}(t) \cdot T} \quad (4)$$

The income $I_{noMarket}(t)$ without CR market participation provides the benchmark of fluctuating RES under the RES support scheme of direct marketing. It is calculated from the trading on the day-ahead spot market. Corrections of schedule deviations are traded on the intraday market only.

b) Profit maximizing bids

The possible revenue of the fluctuating RES generators in the CR market could be maximized with a market price based bidding strategy, which sets it apart from the opportunity cost based approach. Market information is available in the hindcasting approach through the merit-order lists of the CR market. This creates bids derived from the market data that are as high as possible and are still accepted in the market. The market price based capacity price CP_{mp} is the value of the monotonous function f(C) of the capacity C(p) at the merit-order position p for the product period T. The merit-order position p is determined by the total capacity of the merit-order list C_{max} minus the offerable amount P_{offer}. Since real merit-order lists have discrete bid sizes, the functional relationship CP=f(C) between the price and the capacity is processed numerically in REBal.

$$CP_{mp}(T)=f(C(p)) \quad (5)$$

3) Energy prices

The energy price of the bid determines the price paid when the unit is dispatched in the CR market. The opportunity cost based energy prices are mostly dependent on the underlying feed-in tariff of the wind farms and PV systems. In this paper, they shall be equal to the payments by the RES support scheme in Euro per megawatt hour (EUR/MWh). The market price based energy price is determined using the same principle as the capacity prices.

B. Market participation of fluctuating RES generators in the control reserve market

1) Matching the bids with the existing bids in the market

The two different sets of bids by the fluctuating RES generators from the previous step are entered in the existing merit-order lists of the negative SCR or TCR markets. The bids are accepted as long they are cheaper than the existing bids in the market, replacing the current bid in the merit-order list. Since they are already based on the market data, bids from the profit maximization approach will always be accepted.

Each individual bid in the existing merit-order list C(p) at the position p for each product period T is checked for this condition. The bids are replaced according to the following condition in (6), starting with the highest bid position p=n. CP_{bid} for the auction time T is the capacity price of the fluctuating RES generators from the previous step. It replaces the existing capacity price bids in the merit-order list CP(p,T) if the price is lower and the offerable amount P_{Offer} hasn't been exhausted in the previous iteration.

$$\forall CP_{bid}(T)<CP(p,T) \vee \sum_{p=n}^{1} C(p,T)\leq P_{Offer} \rightarrow CP(p,T)\doteq CP_{bid}(T) \quad (6)$$

The new merit-order lists are called $CP_{RES}(p,T)$. The merit-order list from the cost-based approach is called $CP_{RES,op}(p,T)$, the market price based approach $CP_{RES,mp}(p,T)$. Energy bids are replaced, if the capacity bids are replaced.

2) Economics of fluctuating RES generators in the control reserve markets

A cost calculation using a full dispatch simulation is performed to assess the economic impact of the participation of fluctuating RES generators in the hindcast model. The original merit-older lists CP(p,T) are used as a benchmark and compared to the situation that results from the participation of the new generators in the CR market.

The effects of fluctuating RES in the CR markets can be quantified with the help of welfare economics. The total welfare consists of the consumer surplus and the producer surplus. The CR market requires the adaption of the welfare economics theory due to the presence of strategic bidding and the pay-as-bid pricing mechanism.

The changes in the market lead to a shift of the supply function SF_{BM} (benchmark supply function) towards SF_{OP} (opportunity cost based supply function) or SF_{MP} (market price based supply function). SF_{OP} is the shape of the supply function when the fluctuation RES bid according to their opportunity costs whereas SF_{MP} is the shape of the supply function with the profit maximizing market price approach. The demand function DF is completely inelastic in the modelling.

The RES generator does not generate additional revenue with bidding along SF_{OP}. However, cost saving potentials in the form of area A, B and C are accessible by the power system. These would reduce the cost of the CR procurement and can be called the merit-order effect in the CR market, if looked at from the demand side. With the market price based supply function SF_{MP}, additional income for the fluctuating RES generators can be accessed, which is equal to the area B in the figure below. In this case, the cost saving potential in the power system is equal to area A and C. This methodology can be equally applied to the energy prices with the difference that DF is variable over time, as the dispatch signal changes.

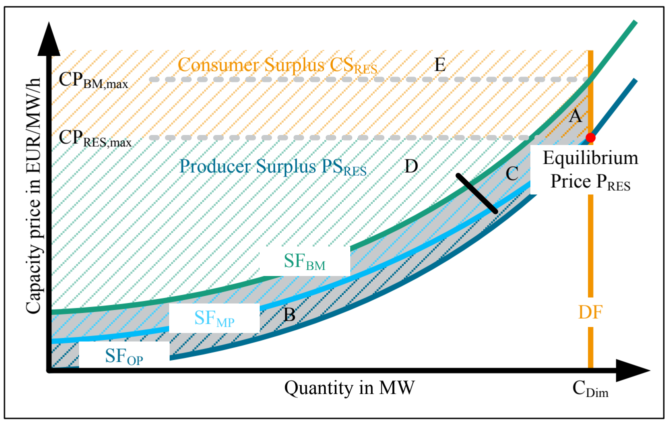

Figure 1. Supply and demand functions for the bids in the control reserve market and with bids from the fluctuating RES generators (OP and MP).

The possible additional income of the fluctuating RES generators is presented in the results section of this paper. The cost saving potentials are omitted at this point and will be presented later. Combining the cost saving potential with the additional income would allow identifying the welfare gain.

C. Data

The data used span from the year 2010 to 2014. All data are processed with the time zone UTC+1 (CEST). The price information of the wholesale electricity market are obtained from EPEX SPOT [15]. The balancing energy price (reBAP) has to be paid for schedule deviations by the balancing responsible parties (BRP). It is calculated by the German TSOs [16] and can be acquired at their website regelleistung.net. The same applies for the CR merit-order lists and the dispatch of SCR and TCR. Feed-in and forecast time series of five different portfolios of fluctuating RES generators in total are used in the assessment. Forecast and feed-in time series of a 30 GW pool wind farms and a 30 GW pool of PV systems can be obtained from [17]. Data of 1 GW pool of individual wind farms were gathered in the project "Regelenergie durch Windkraftanlagen" [12]. Data on a 1 GW pool of existing individual PV systems was obtained in several research projects at the Fraunhofer IWES, in collaboration with project partners. The German 1 GW pool of offshore wind farms uses simulated data according to [18].

D. Modelling assumptions

The entire portfolio of the German wind farms and PV systems can be pooled, disregarding grid connection issues or the allocation to control areas. It is assumed that prequalification procedure can be fulfilled by all fluctuating RES generators in the pool and that all units in it are capable of delivering CR. The CR market has daily tendering already implemented. Fluctuations on a shorter basis than 15 minutes are not accounted for. Feed-in tariffs (FIT) are equal for all units in the pool. The assumed FIT for onshore wind farms is 89.5 EUR/MWh, 150 EUR/MWh for offshore wind farms and 90 EUR/MWh for PV systems. The market participants have a perfect price forecast. The available active power proof method is applied (see [12]).

III. Results

Based on the previously presented methodology, the potentials of providing CR for different fluctuating RES generators are shown. The results shown in this chapter are focussed on the negative SCR and TCR market with a product length of four hours and daily tendering of the individual products. These conditions are most likely to be implemented by the German regulator BNetzA during the ongoing consultation process [19]. The negative reserve market is chosen since the economic incentives for participation in this market are the highest.

A. Technical potentials

The probabilistic forecasts in (1) for the day-ahead case and (2) for the intraday case are used to calculate the offers for the CR market by the fluctuating RES. These RES generators include a German 30 GW pool of onshore wind farms, a 30 GW pool of PV systems, a 1 GW of offshore wind farms, a 1 GW of onshore wind farms and a 1 GW pool of PV systems. The probabilistic forecasts generated are combined with the product length in the market and the offerable quantities are determined using (3).

The offerable amount that could be brought to the market varies highly from hour to hour (see e.g. [11]). For reasons of comparability between the different pool types, it is favourable to display the potentials as aggregated values. The summarized annual offerable amount in relation to their annual feed-in removes the impact of the pool size, as shown in Fig. 2 for the day-ahead forecast (top) and the intraday forecast (bottom). The given values are the average value for different years available for each pool type. The 30 GW onshore wind farm pool is depicted in blue, the 1 GW onshore wind farm pool in dark blue, the offshore wind farms pool in green, the 30 GW pool of PV systems in yellow and the 1 GW pool of PV systems in orange. From left to right levels of reliability are shown from 95 % to 99.994 %. The numbers on the bars depict the energy content of the offerable capacity in TWh.

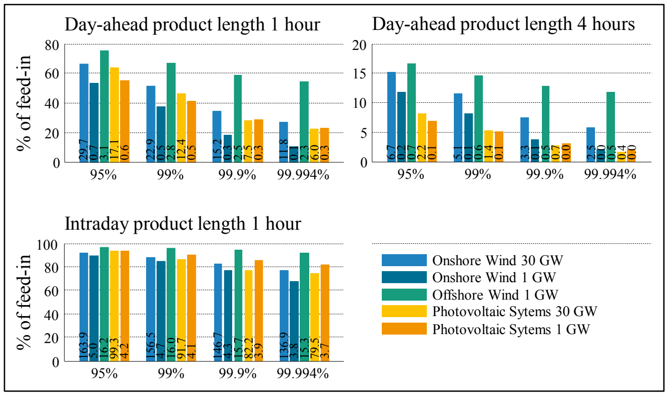

Figure 2. Offerable potentials for control reserve provision as percentage of the annual feed-in for different pools fluctuating RES generators.

With product lengths of more than four hours, the potential of providing CR for wind farms is increasingly limited. The effect is amplified for smaller wind farm pools, as the forecast error is highly significant. PV systems have already limited capabilities to provide CR with product length of four hours or more. The dependencies on pool size and level of reliability for the probabilistic intraday forecast are significantly lower. This is caused by the different shape of the forecast error distribution, which is narrower. Forecast errors are less pronounced for short time horizons than for longer time horizons. The influence of the pool size decreases as the short-term forecast depends on the online feed-in value and feed-in profiles do not differ significantly between the 1 GW and the 30 GW pool.

B. Bids for the control reserve market

The opportunity cost based approach leads to the cheapest bids possible in the CR market with fluctuating RES generators. Since no curtailment is necessary, capacity prices under the available active power proof method for negative CR markets are zero by definition.

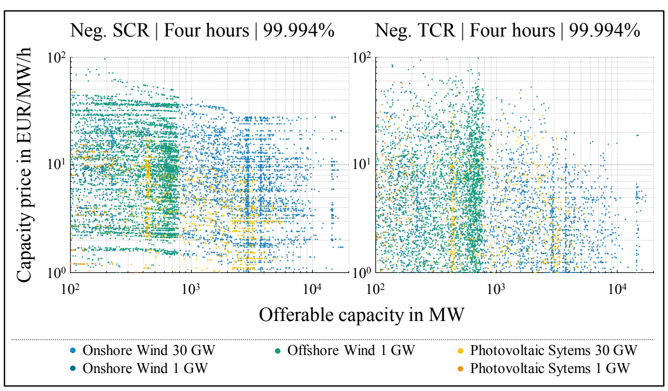

Figure 3. Profit maximizing price/quantity combinations of the capacity price bids for different pools fluctuating RES generators with a level of reliability of 99.994 % for the five different pools of fluctuating RES.

The bids resulting from the profit maximizing bidding approach maximize the achievable additional income by the fluctuating RES generators. The resulting price/quantity combinations of the capacity bids by the chosen portfolios are shown in the log-log scatter plot in Fig. 3. The level of reliability is 99.994%, to ensure that the bids are as reliable as current bids in the market. All bids shown here would have been accepted in the market.

The different portfolios intersect the merit-order lists at different positions, depending on the current potential for delivering CR. This leads to volatile prices over time and differences between the different pools of generators. The market price based bidding strategy leads to no or very little reductions in CR procurement costs from the system's point of view. Since energy price bids depend on the RES support scheme, and the assumed feed-in tariff, they do not have to be depicted at this point.

C. Possible additional income for the fluctuating RES generators

The difference between both pricing approaches in the previous step results in additional income that could be earned through CR market participation. Comparing the capacity and dispatch costs of the CR market, with and without the market participation of fluctuating RES, allows the quantification of the possible additional income as depicted in Fig. 4 below.

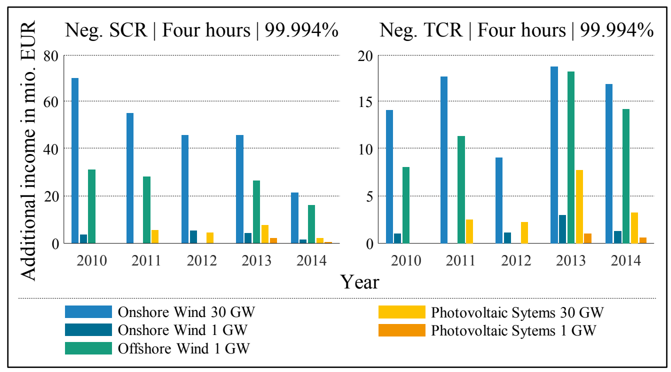

Figure 4. Additional possible income for different fluctuating RES generators in the negative SCR and TCR under realistic market conditions.

Fluctuating RES generators are able to generate significant revenue in the negative SCR and TCR market segments. By assessing the additional revenue over several years, one could conclude that the market potential can be accessed despite changing market conditions and increasing competition. The varying market potential between 2010 and 2014 correlates with the variations in the total market size. Positive CR market segments are not shown in this paper since fluctuating RES generators are not competitive in the current market structure. The following table shows the average values and the range over all years for the different pools, given in EUR/MW$_{inst}$/a.

TABLE I. POSSIBLE ADDITIONAL INCOME OF DIFFERENT POOLS OF FLUCTUATING RES GENERATORS IN THE CONTROL RESERVE MARKET.

Possible additional income in EUR/MW$_{inst}$/a	**Averaged annual possible additional income and its range (in brackets)**				
	30 GW onshore wind farm	***1 GW onshore wind farm***	***1 GW offshore wind farm***	***30 GW PV systems***	***1 GW PV systems***
Secondary negative market	**1,600** (725-2,350)	**3,725** (1,500-5,400)	**25,725** (16,300-31,500)	**160** (70-260)	**1,300** (500-2,100)
Tertiary negative market	**500** (300-625)	**1,625** (1100-3,000)	**12,900** (8,100-18,000)	**130** (70-260)	**800** (600-1,000)

It can be concluded that the fluctuating RES generators will also be able to access the markets' potential in an increasingly competitive environment. The results are highly dependent on factors such as the forecast quality and market regulations. The correlation of the possible income over time in Fig. 4 with the overall market size indicates that the ratio between them can be utilized to estimate the possible additional income in the future by estimating the market volume itself.

IV. Conclusion and Discussion

Considering the variations between the years, it can be concluded that fluctuating RES are able to access the markets value in an increasingly competitive environment. A large dependency on the level of reliability, the product length and the auction lead-time was identified. It is paramount that the product length and lead-time is kept as short as reasonably possible, as the currently discussed changes [19] are insufficient for PV systems. Decreasing overall market sizes lead to decreasing additional income for the new market participants, which suggest a strong correlation between these two factors.

This paper extends earlier results [11, 12] by applying the methodology to several years of data and a large variety of pools of fluctuating RES. This allows comparing the influence of the market on the income opportunities. The methodology presented can also be used to calculate the welfare gain by the introduction of fluctuating RES in the market. This will be shown in later publications.

The result for offshore wind farms, generating on average 12,900 EUR/MW_{inst}/a in the TCR market, are comparable to the findings of Papaefthymiou et al. [20], when the increased competition in the market in the future is considered. The average additional income of all of the other fluctuating RES generators would have been significantly lower, 1,625 EUR/MW_{inst}/a for a 1 GW onshore wind farm pool and 800 EUR/MW_{inst}/a EUR/MW_{inst} for a 1 GW pool of PV systems.

Acknowledgment

The REBal model in this paper was created in different projects at the Fraunhofer IWES. The methodology and results will also be presented in doctoral thesis at the European University of Flensburg, which is currently under review.

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