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# Electricity Grid In-feed from Renewable Sources: A Risk for Pumped-Storage Hydro Plants?

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***Abstract*—The ongoing large-scale deployment of new renewable energy sources (RES), mostly in the form of wind turbines and photovoltaic (PV) units, causes an increasing share of stochastic electricity in-feed, which inevitably has impacts on electricity spot markets. In this paper, an analysis of the impacts of RES in-feeds on the spot market price spread as well as its volatility is presented. The potential risk that these impacts on spot prices may pose for the business model of pumped-storage hydro plants is discussed. Furthermore, the dependency of spot prices on wind turbine and PV electricity in-feeds are studied. The presented analysis focuses on the situation in Germany with its, in relative and absolute terms, high share of stochastic electricity in-feed and its mature spot market.**

## I. INTRODUCTION

In the early 1990s, many European governments initiated a transformation process in their power markets, moving from national monopolies of mostly publicly-owned companies towards liberalized and increasingly European power markets. At around the same time, the first government-support schemes for the large-scale deployment of RES were introduced. From the different types of initially proposed support schemes, feed-in tariff (FIT) schemes have emerged as the most popular type and have since been widely implemented worldwide [1]. The most prominent FIT scheme is the German ”Erneuerbare-Energien-Gesetz” (EEG), introduced in 2000 as a replacement for its predecessor, the ”Stromeinspeisungsgesetz” from 1991.

Thanks to the initial EEG and its later revisions, a very favorable investment climate for renewable electricity sources such as wind turbines, biomass-fired and PV generation units was created. Besides granting a fixed FIT for renewable generated electricity over the course of 20 years, the EEG stipulates guaranteed grid connection and in-feed priority for newly installed RES units. These measures have induced significant investments into RES. By year-end 2009, Germany's cumulative stochastic RES electricity generation capacity totalled 25.7 GW from wind turbines and 9.8 GW from grid-connected PV [2], [3]. A further significant increase of German RES capacity, notably in the form of PV, is estimated for 2010. The estimated cumulative stochastic RES generation capacity for year-end 2010 is around 27.2 GW for wind turbines [4] and 17.2 GW (low est.) to 18.6 GW (high est.) for grid-connected PV [5]–[7]. An illustration of the rapid RES deployment in Germany since 1990 is depicted in Fig. 1.

Germany's electricity spot market is part of the European Power Exchange (EPEX), a multi-national continental European electricity spot market split into three different market zones (France, Germany & Austria and Switzerland) [8].
By the stipulations of the EEG, all of Germany's subsidized renewable electricity production has to be completely inserted into the EPEX's combined German-Austrian spot market by each German transmission system operator (TSO). This is accomplished by bidding renewable electricity into the spot market's merit-order curve using the minimum price bid (currently -3000 €/MWh) [9].

Thus, all market participants, e.g. large producers, traders and public utilities, are to some degree affected by the impact that renewable electricity in-feed has on electricity spot prices. This impact is visible notably as increased spot market volatility. This in turn leads to updates of hourly price forward curve (HPFC) models, which all market participants use as an arbitrage-free instrument for pricing electricity contracts on an hourly basis [10].

The stochastic character of power in-feed from intermittent RES, e.g. wind turbines and PV installations, as well as the resulting theoretic (and actual) impacts of RES power in-feed on the spot market's merit-order curve and prices have been discussed in the past. The focus thus far has been on RES in-feed from wind turbines [11], [12].

In this paper, we discuss in more detail the time-dependence between intermittent RES in-feed from wind turbines and PV units. A special focus is here on German PV in-feed, for which only recently detailed data has become available [13]. Furthermore, an assessment of the correlation of RES in-feed with electricity spot market prices is presented. The impacts of RES power in-feed on EPEX spot price profiles regarding the intra-day profiles and low-frequency seasonality are analyzed.

The remainder of this article is organized as follows: First, the underlying data sets for the analysis are presented and briefly discussed in Section II. The risk to the traditional business case of pumped-storage hydro plants (price arbitrage) is discussed in Section III. Further analysis on the RES in-feed prediction errors is presented in Section IV. Finally, Section V concludes the presented results.

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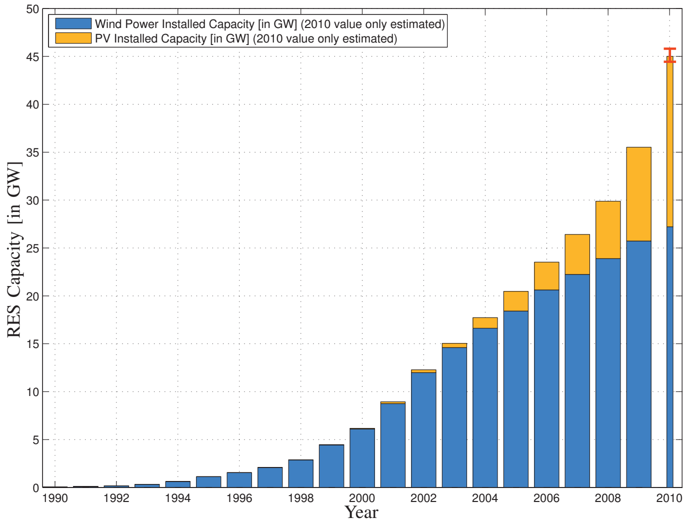


Fig. 1. Development of installed RES power capacity (1990–2010).

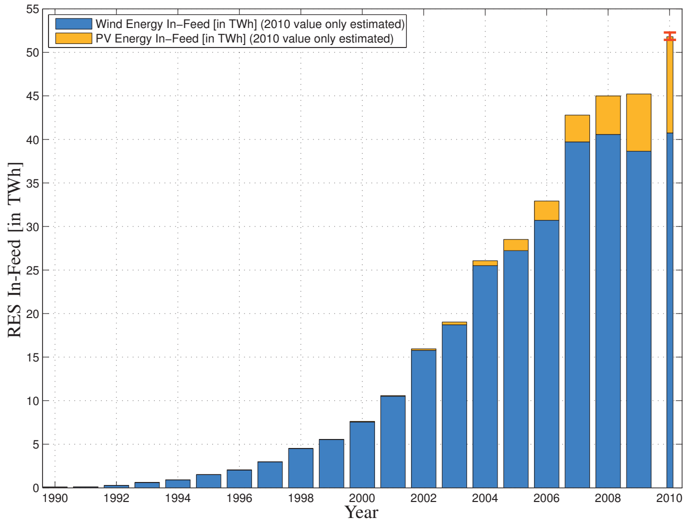


Fig. 2. Development of annual RES electricity in-feed (1990–2010).

## II. DATA SETS

The proposed methods are tested using EPEX spot price data from the German-Austrian power market as well as wind turbine and PV power in-feed data.

Day-ahead EPEX spot market prices of the German-Austrian spot price zone, given on an hourly basis, are used. They have been provided by the European Energy Exchange (EEX) [14] for the years 2006-2010. Wind and PV electricity in-feed data is taken from TenneT's German TSO zone (formerly Transpower TSO zone), as provided in [15]. The data contains the day-ahead prediction as well as realized in-feed time-series of both wind and PV in-feed on a 15-minute basis. The duration of the data is shown in Table I. The scope of the analysis has to be limited to the shortest electricity in-feed time-series available for analysis. This is the time-series for PV power in-feed, which only started in March 2010.

However, the amount of available transparency data increases rapidly. Thus the analysis presented here for the given data set, will also be performed on new data with a longer history and fore more regions, as soon as it becomes available.

TABLE I
WIND AND PV DATA AVAILABILITY

| | begin | end |
|---|---|---|
| EPEX day-ahead spot price | 1-Jan-2006 | 31-Dec-2010 |
| wind in-feed realized | 1-Mar-2010 | 31-Dec-2010 |
| wind in-feed predicted | 1-Mar-2010 | 31-Dec-2010 |
| PV in-feed realized | 1-Mar-2010 | 31-Dec-2010 |
| PV in-feed predicted | 1-Mar-2010 | 31-Dec-2010 |

The day-light saving time changes have been considered.

## III. RISK ANALYSIS FOR PUMPED-STORAGE UNITS

In this section, we discuss the risk to pumped-storage plants because of wind and PV in-feed.

### A. Pumped-Storage Units Business Concept

Hydro power plants can be separated in two major groups 1.) run-of-river power plants and 2.) pumped-storage plants. Run-of-river power plants turbine natural inflows, mostly from rivers. The pumped-storage plants have very little to no natural inflows and rely mainly on water which is pumped uphill into the storage. The water is pumped during periods of low electricity prices (usually night-time) and turbined during high electricity price periods (usually peak hours). Therefore, the traditional business model of pumped-storage hydro plants is based largely on statistical electricity price arbitrage between day-time and night-time. Besides electricity price arbitrage, pumped-storage units are increasingly providing lucrative ancillary services to the grid. To assess whether or not the core business of pumped-storage units is at risk due to increasing RES electricity in-feed, two valuation approaches are used.

A pumped-storage plant can be handled as a complex call option and we address the deterministic and the stochastic approach. In the deterministic approach, we evaluate the power plant arbitrage opportunity based on the peak-base spread, which reflects the inner value of the option. The stochastic approach also takes optionality, the possibility to pump or turbine at a certain electricity price level, into account. This approach represents the option price or optional value of the option. The valuation of pumped-storage plant optional value requires complex methods such as stochastic dynamic programming, which are not part of this paper. Because of the possibility to choose, the stochastic value of the power plant must be equal or higher than the deterministic value.

### B. Deterministic Approach: Analysis of Intra-Day Spot Price Profile with Increasing RES In-feed

The evolution of the intra-day spot price profile over the last five years has been analyzed. The notation used in the remainder of this article is the following: The day index for realized days is given by $t$, the index for hours by $j$, the 15 minute intra-hour time step index by $g$ and the year index by $k$. We denote by $S_{t,j}$ the spot data at day $t$ for hour $j$ and by

$I_{t,j,g}$ the 15 minute in-feed data at day $t$ for hour $h$ and the 15 minute block $g$.

The spot price and in-feed data is clustered in several clusters $\mathfrak{U}_{u,k}$, where $k$ denotes the years and $u$ the days corresponding to the cluster. The predicted in-feed data is denoted by $I_{t,j}^{(p)}$, whereas the actually realized in-feed data is denoted by $I_{t,j}^{(r)}$. An estimated value is denoted by $\hat{\Box}$ and the average value by $\bar{\Box}$.

In-feed data is provided in 15 minute time steps, whereas spot prices are hourly-based. The realized hourly electricity in-feed is calculated as

$$\hat{I}_{t,j}^{(r)} = \hat{\mathrm{E}}_g[I_{t,j,g}^{(r)}] \tag{1}$$

and the predicted hourly day-ahead electricity in-feed as

$$\hat{I}_{t,j}^{(p)} = \hat{\mathrm{E}}_g[I_{t,j,g}^{(p)}]\,. \tag{2}$$

The definitions are equivalent for both wind and PV power in-feed.

The relative hourly profiles $\bar{h}_{u,k}$ are calculated for the clusters $\mathfrak{U}_{u,k}$, where $u$ defines a specific set of the full set $\mathfrak{U}$ and $k$ the years of the cluster. For each calculation the specific set $\mathfrak{U}_{u,k}$ is used.

Three cluster sets have been used for calculations: The first cluster $u$ contains all hours of one full year from the set of the given five years (2006-2010), the second cluster only contains the hours of the month of January of every year and the third cluster only contains the hours of the month of July of every year. Altogether 15 clusters $\mathfrak{U}_{u=1\ldots3,k=1\ldots5}$ have been constructed. The hourly profile is then calculated using

$$\hat{\bar{H}}_{u,k} = \hat{\mathrm{E}}_t[S_{t\,|t\in\mathfrak{U}_{u,k},j}]\,, \tag{3}$$

where $\mathfrak{U}_{u,k}$ contains the data of the given clusters $u, k$. The clusters $\mathfrak{U}_{u,k}$ together form the entire set $\mathfrak{U}$.

The yearly-averaged relative hourly spot price profile $\bar{h}_{u,k}$ is calculated using

$$\hat{\bar{h}}_{u,k} = \hat{\mathrm{E}}_t\left[\frac{S_{t\,|t\in\mathfrak{U}_{u,k},j}}{\hat{\mathrm{E}}_j[S_{t\,|t\in\mathfrak{U}_{u,k},j}]}\right]. \tag{4}$$

Fig. 3 shows the development of the yearly-averaged relative daily spot price profile $\bar{h}_{u,k}$. The figure also depicts the averaged hourly PV electricity in-feed over the course of a full year. As can be seen, the peak PV in-feed coincides with the relative hourly peak spot price, which occurs at noon ($13^{th}$ hour).

During the last five years the relative hourly peak spot prices have, with one exception, continuously decreased from a value of 1.46 (2006) to 1.24 (2010), a reduction of 15.1%. At the same time, yearly PV electricity in-feed has increased five-fold, from around 2 TWh to 10 TWh. Since PV in-feed follows a seasonal pattern, winter and summer time have to be looked at separately, as was done in Fig. 4. As the impact of PV in-feed on the spot market's merit-order curve is most dominant at noon, the here presented data strongly suggests that the reduction of the average spot price peak at noon can, at least partially, be explained by the growing PV in-feed.

As can be seen in Fig. 3, the averaged spot price profile for the full year of 2007 exhibits a high peak price at noon. One possible explanation for this effect is the marked rise of spot prices combined with high volatility in the second half of 2007, Fig. 5. Part of this spot price increase in 2007-08 was driven by the general hike of energy commodities (crude oil, natural gas, coal) at that time.

Besides the decrease of the peak hour's spot price, also the ratio between peak and off-peak spot prices, the so-called peak off-peak spread $\zeta$, as defined by

$$\zeta = \frac{\text{avg peak price}}{\text{avg off-peak price}}\,, \tag{5}$$

has markedly decreased from a value of 1.59 (2006) to 1.33 (2010), a reduction of 16.4%. Again, a significant outlier is visible for the year 2007, as shown in Table II.

The significant decrease of the peak off-peak spread $\zeta$ poses a risk to pumped-storage hydro plants: If $\zeta$ decreases, then price arbitrage between peak and off-peak hours becomes less profitable (assuming all other factors stay the same).

As an illustration a small case study is used: Given is a pumped-hydro unit with an assumed round-trip efficiency,. accounting the occurring energy for both pumping water uphill into the storage lake and lager on turbine water downhill, of $\eta = 80\%$. The profitability of a price arbitrage operation strategy for this hydro unit will then, from a deterministic viewpoint, depend on the average relative peak base spread $\zeta$ as well as the average spot price $P_{spot}^{base}$ (= base spot price) for a given year. The cost of the energy lost during the storage operation, given by the efficiency $\eta$, has to be accounted for as well, i.e. $\frac{1}{\eta} = 1.25$ units of electricity need to be pumped up for every unit of electricity that shall be turbined at a later stage. This leads to the following term for calculating the average net arbitrage potential $\Delta_{net}$ for a given year:

$$\begin{aligned}\Delta_{net} &= \left(\frac{\text{avg peak price} - \frac{1}{\eta}\cdot\text{avg off-peak price}}{\text{avg off-peak price}}\right)\cdot P_{spot}^{base}\\ &= \left(\zeta - \frac{1}{\eta}\right)\cdot P_{spot}^{base}\,.\end{aligned} \tag{6}$$

According to the data analyzed, the net arbitrage potential fell from 17.06 $\frac{€}{MWh}$ (2006) to 3.71 $\frac{€}{MWh}$ (2010), a decline of 78%, see also Table II.

Judging from the results for the net arbitrage potential $\Delta_{net}$, the traditional business model of pumped-storage hydro units is at risk. The peak off-peak spread $\zeta$ seems to be the most important parameter for the potential earning of hydro pump storage plants. However, both the evolution of $\zeta$ as well as the yearly averaged base spot price do influence $\Delta_{net}$, thus rendering its value, and with it the business outlook for pumped-storage hydro units, highly volatile.

However, the presented results have been derived having a deterministic point of view. The stochastic value (optional value) of a hydro-pumped storage plant is higher than its deterministic value (inner value), as will be discussed next.

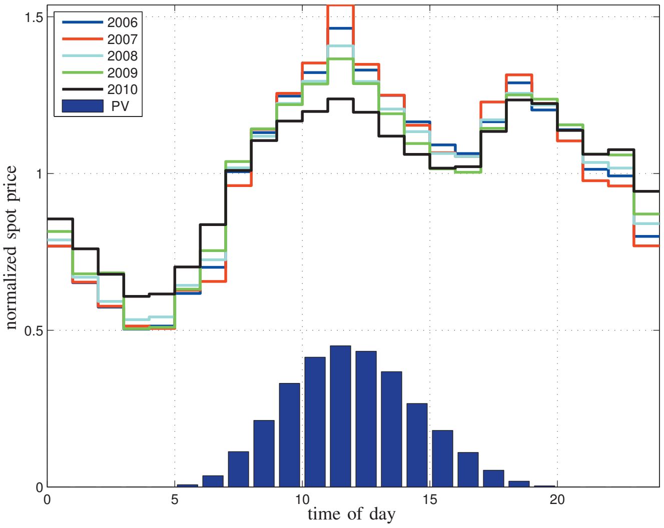
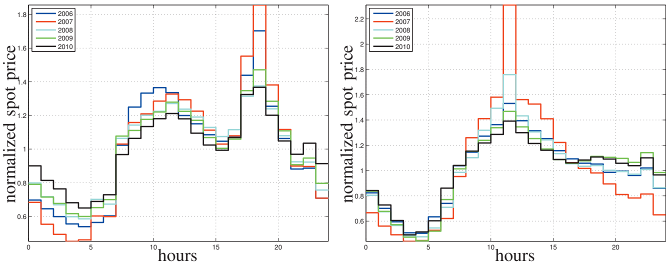


Fig. 3. Hourly average over the full year for 2006 to 2010



(a) Hourly average, January 2006–10. (b) Hourly average, June 2006–10.

Fig. 4. Mean of hours of the years 2006 to 2010 in June

TABLE II
YEARLY PEAK BASE SPREAD $\zeta$ AND NET ARBITRAGE POTENTIAL $\Delta_{net}$

| Year | $\zeta$ | $\Delta_{net}$ $[\frac{€}{MWh}]$ | $P^{base}_{spot}$ $[\frac{€}{MWh}]$ |
|---|---|---|---|
| 2006 | 1.59 | 17.06 | 50.79 |
| 2007 | 1.64 | 15.00 | 37.99 |
| 2008 | 1.51 | 17.12 | 65.76 |
| 2009 | 1.46 | 8.09 | 38.85 |
| 2010 | 1.33 | 3.71 | 44.49 |

### *C. Stochastic Approach: Analysis of Intra-Day Spot Price Volatility with Increasing RES In-feed*

The stochastic value (optional value) of a hydro-pumped storage plant is directly dependent on the volatility, and with it the evolution, of the electricity spot price. In Fig. 5 both the EPEX spot price evolution as well as its dynamic exponentially weighted moving average (EWMA) volatility are presented. The spot price volatility has in general decreased over the time frame 2006–2010, from an average of 0.34 (2006) to 0.21 (2010), a reduction of 37.1%. As can be seen, tail events such as sudden large positive or negative spot price jumps, seen in 2006 and 2009 respectively, do strongly influence the calculated volatility value.

In general, a decreasing volatility leads also to a reduction of the stochastic value (optional value) of stored electricity. However, as long as the volatility is not zero, the optional value of a pumped-storage hydro plant will remain higher than the inner value (the deterministic averaged spot price spread).

For the risk assessment this means that a stochastic (optional value) approach is more favorable than a mere deterministic (inner) value approach, because the optional value of stored water is higher than the inner value. Nevertheless, the evolution of the volatility over the last five years indicates a trend towards falling optional values. Yet another indication that price arbitrage as the core business for pumped-storage hydro stations is at risk in the longer term.

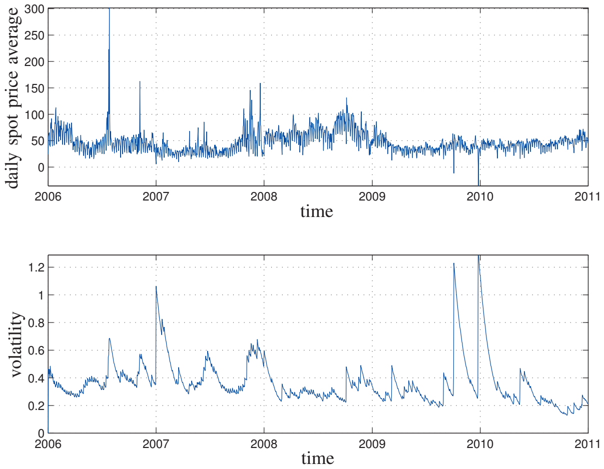


Fig. 5. Daily average spot price and its dynamic EWMA volatility

## IV. ANALYSIS OF THE PREDICTION ERROR

In this section we analyze the prediction error, which is an important parameter for power plant scheduling, since the power plant schedule is based on the day-ahead RES power in-feed and load demand prediction. The difference between intra-day prediction and realized in-feed must be covered by intra-day spot market trading. The remaining small deviation is balanced via ancillary services mainly tertiary frequency control [16]. In both cases, spot market coverage or ancillary services market and liquidity risk can result in high costs. The analysis was performed on wind, PV and the combined in-feed, where the combined in-feed is calculated as the sum of wind and PV in-feed. The prediction error $\phi$ is defined as

$$\phi_{t,j} = I^{r}_{t,j} - I^{p}_{t,j}. \qquad (7)$$

*1) Prediction Error Distribution Analysis:* PV in-feed is zero during night hours. Therefore, we compare wind and PV time series only when the PV in-feed is non-zero. Hourly average calculates are used as shown in Eq. (1). Fig. 6, 7(a) and 7(b) show the histograms of the hourly prediction error distributions compared to the corresponding Normal distribution. Table III shows some properties of the prediction error distributions. As shown in the figures the assumption of the Normal distribution, $\mathcal{N}(\mu, \sigma^2)$, described by the mean $\mu$ and the variance $\sigma^2$ as the error distribution, is rejected. Instead heavy tailed and skewed distributions must be used for modeling and risk management [17].

TABLE III
DISTRIBUTION PROPERTIES

| | wind | PV | combined |
|---|---|---|---|
| mean | -0.40199 | -0.64184 | -0.7883 |
| median | -0.18422 | -0.029142 | -0.029142 |
| variance | 0.75304 | 37.3922 | 1332.6262 |
| skewness | -2.768 | -39.8382 | -66.3752 |
| kurtosis | 14.4437 | 2064.4995 | 4418.662 |

For many purposes, especially risk management as well as financial and physical delivery, events with high deviation are important. Therefore we discuss 5% and 1% quantiles of the distribution, which are the widely used quantiles in risk management. Hence the prediction can be higher or lower than the realization and must be balanced to the schedule, negative and positive prediction error quantiles are important. Speaking in financial terms, the prediction error can be a long or short position, therefore, we measure the 1%, 5%, 95% and 99% quantiles or from a portfolio position perspective the 1%, 5%, 95% and 99% Value-at-Risk (VaR).

TABLE IV
QUANTILES AND MIN/MAX OF THE DISTRIBUTIONS IN [MW]

| | wind | PV | combined |
|---|---|---|---|
| 95% percentile | 973.5 | 479.6875 | 1120.625 |
| 5% percentile | -1202 | -557.9375 | -1405.75 |
| 99% percentile | 1893.75 | 921.725 | 2245.75 |
| 1% percentile | -2116.5 | -1090.35 | -2574.125 |
| maximum | 4006.5 | 2598 | 4011.5 |
| minimum | -4030 | -2838.75 | -4802 |

Table IV shows the 1%, 5%, 95% and 99% quantiles, where the 1%, 5% quantiles exhibit a higher prediction than realized (negative prediction error), while the 95% and 99% quantiles show a lower prediction than realized (positive prediction error). The combined quantile of 5% and 95% is around 1.2 GW, which would represent the net generation of one large modern nuclear power plant.

The prediction error is calculated independently for every hour. The prediction errors of time periods larger than hourly periods can be calculated by the convolution of the hourly prediction error distribution.

*2) Measurement Error Analysis:* The prediction error distributions in Section IV-1 are calculated on an hourly basis.

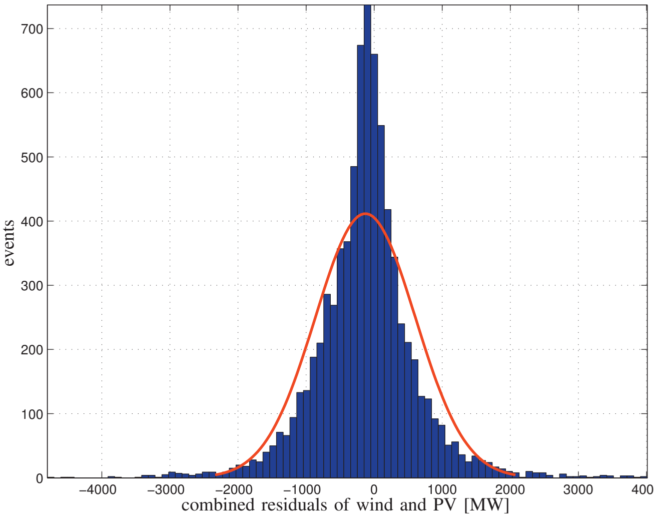
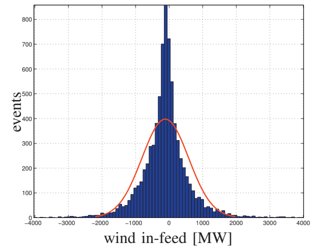
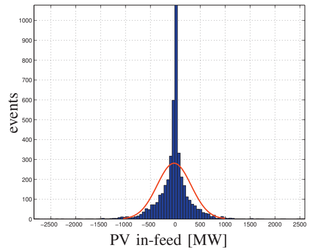


Fig. 6. Distribution of the combined wind and PV in-feed residuals.



(a) Distribution of the wind in-feed residuals.



(b) Distribution of the PV in-feed residuals.

To measure the prediction quality over the full sample set, a widely used method is the mean square error (MSE),

$$\text{MSE} = \frac{1}{N}\sigma^2 , \tag{8}$$

where $N$ is the number of samples [18].

As the MSE is defined by the variance, this measure inherently assumes normal distributed data. As discussed in [19] and [20], measures assuming the normal distribution are not robust against non-normal distributed data. Given the distributions parameter of the prediction error in Table III, and the histograms in Fig. 6, 7(a) and 7(b) the assumption of the normal distribution does not hold. Therefore, the mean absolute prediction error (MAPE), another measure which does not assume normal distributed data was used. The MAPE is defined as

$$\text{MAPE} = \frac{1}{N}\sum_{t=1}^{n}\left|\frac{I^r_{t,h} - I^p_{t,h}}{I^r_{t,h}}\right| , \tag{9}$$

where $N$ is the number of samples [21].

Table V shows MSE and MAPE of wind, PV and combined in-feed. The prediction quality for wind is significantly better for both measures. Possible explanations for the better prediction quality of wind in-feed are the strong auto-correlation of wind hours and the longer experience in wind predictions. The higher dynamics of sky cover and thunderstorms, especially in the summer, render PV in-feed predictions more difficult.

TABLE V
PREDICTION ERROR CHARACTERISTICS

| | wind | PV | combined |
|---|---|---|---|
| MSE | $1.6e^{-4}$ | $8.5e^{-3}$ | $8.4e^{-3}$ |
| MAPE | 0.56 | 0.86 | 0.91 |

## V. CONCLUSION

In this paper we analyzed the influence of the increasing electricity in-feed of wind and PV generation on the EPEX spot prices of the German-Austrian price zone. The data analysis strongly suggests that RES in-feed, notably from PV installations, significantly depresses the electricity spot price's intra-day shape around noon. The spot price peak/off-peak spread $\zeta$ is significantly reduced. This effect in turn significantly diminishes the net arbitrage potential $\Delta_{net}$, i.e. the theoretic deterministic peak/off-peak spread minus the cost from inherent energy losses that occur when using pumped-storage hydro plants. For a hydro-pumped storage unit with a storage cycle efficiency if $\eta = 80\%$, a net arbitrage potential $\Delta_{net}$ of currently only $3-4€/MWh$ can be achieved. Would this trend continue, then spot price arbitrage strategies of pump-storage units would eventually become non-profitable. It has to be noted, however, that our main focus here is a deterministic approach, based on stored electricity's inner value. A stochastic approach, based on the optional value of stored electricity shows a more favorable picture, although the trend is also towards diminishing arbitrage returns.

The article furthermore studied the dependencies of spot prices on RES electricity in-feed. Wind in-feed shows a slightly decreasing affect on spot prices. PV in-feed occurs when the spot price has its daily peak, i.e. around noon time. This indicates that the price reduction effect of PV in-feed on the spot price's merit-order curve should be comparatively stronger than the effect of wind in-feed (per unit of electricity feed-in).

The study concludes with an analysis of the prediction error of wind and PV in-feed. Both prediction error distributions show a large amount of heavy tails and an overall better prediction quality for wind in-feed than for PV in-feed.

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