Revisiting the Merit-Order Effect of Renewable Energy Sources

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Abstract

An on-going debate in the energy economics and power market community has raised the question if energy-only power markets are increasingly failing due to growing in-feed shares from subsidized renewable energy sources (RES). The short answer to this is: No, they are not failing.

Energy-based power markets are, however, facing several market distortions, namely from the gap between the electricity volume traded at spot markets versus the overall electricity consumption as well as the (wrong) regulatory assumption that variable RES generation, i.e., wind and PV, truly have zero marginal operation costs. We show that both effects overamplify the well-known merit-order effect of RES power in-feed beyond a level that is explainable by underlying physical realities, i.e., thermal power plants being willing to accept negative electricity prices to be able to stay online due to considerations of wear & tear and start-stop constraints.

In this paper we analyze the impacts of wind and PV power in-feed on the spot market for a region that is already today experiencing significant FIT-subsidized RES power in-feed (≈20%), the German-Austrian market zone of the European Power Exchange (EPEX).

We show a comparison of the FIT-subsidized renewable energy sources (RES) energy production volume to the spot market volume and the overall load demand. Furthermore, a spot market analysis based on the assumption that RES units have to feed-in with their assumed true marginal costs, i.e., operation, maintenance and balancing costs, is performed. Our analysis results show that, if the necessary regulatory adaptations are taken, i.e., increasing the spot market’s share of overall load demand and using the true marginal costs of RES units in the merit-order, energy-based power markets can remain functional despite high RES power in-feed.

I. INTRODUCTION

Around the same time as the liberalization of many of the European Electricity markets in the early 1990s, government support schemes with the specific goal of promoting large-scale deployment of renewable energy sources (RES) were introduced. The German Renewable Energy Act, ”Erneuerbare-Energien-Gesetz” (EEG), a well-known support scheme, provides a favorable feed-in tariff (FIT) for a variety of renewable energy sources (RES) since the year 2000 and builds on the good experience with its predecessor, the Stromeinspeisungsgesetz from 1991. It gives priority to electric power in-feed from RES over power in-feed from conventional power plants, i.e., fossil- and nuclear-fueled thermal and old, often large hydro-based power plants. This favorable investment case has generated installed capacities of more than 30 GW each for wind and photovoltaic (PV) units by year-end 2012. The evolution of installed variable RES capacities and annual energy production in Germany from 1990 to 2012 [1], including an outlook till 2017 [2], are shown in Fig. 1–2 The original goal of the FIT, i.e., large-scale RES deployment (Fig. 1) and significant RES energy shares (Fig. 2) is achieved.

With a combined installed capacity of wind & PV units of around 65 GW, roughly the same as the average load demand in Germany (63-68 GW dependant on load demand measure), wind & PV units clearly cannot be treated as exotic, marginal electricity sources anymore. The current RES production has already significant effects on the power market, notably in the form of the so-called merit-order effect. Especially the decoupling of spot market prices and RES in-feed due to FIT regulations, results in lower average spot price levels and also in negative spot prices for several hours each month. One effect of this is that flexible power plants such as gas-fired units cannot be operated profitably because peak spot prices are too often below their marginal operation costs. Another effect is that due to the also decreasing spread
of peak/base spot prices, energy storage facilities, i.e., pumped storage hydro plants (PSHP) cannot be operated profitably either [3].

While in the long run the support schemes for RES units are likely to be phased-out, and RES units will thus have to compete in a normal market setup, in the mid-term the market structure has to be adapted to the increasing effects of RES deployment. For the subsequent investigation the two relevant perspectives have to be taken into account:

1) **Producer perspective**: How to integrate RES in-feed into the market to limit the negative effects on dispatchable base and peak load power plants?
2) **Consumer perspective**: How to lower the cost of FIT schemes and enable a transition to a less subsidized and, eventually, a true market environment?

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**Fig. 1.** Evolution of installed capacity of wind and PV units in Germany.

**Fig. 2.** Evolution of annual in-feed of wind and PV units in Germany.

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### A. Producer Perspective

In Germany, and similarly in Austria, all FIT-supported RES power in-feed is settled at the spot market of the European Power Exchange (EPEX) either directly, e.g. in the form of power supply bids, or indirectly, e.g. in the form of reduced load demand bids. This construction results in two major effects on the spot market. Firstly, because of the decoupling of FIT-supported RES in-feed from spot prices, the average market price decreases, since all those bids will be located on the negative side of the supply curve, e.g. going as low as $-3000 \text{\euro/MWh}$, in order to guarantee the settlement. Besides the in general lower
spot price levels, negative spot prices tend to occur, especially in *low demand & high wind* situations. Secondly, because of the large deployment of PV, the peak/base spread is decreasing [6].

Short- and mid-term, a completely RES based production cannot provide the necessary production volume as well as reliability for fulfilling the load demand. Therefore, conventional power plants for base load and peak load are necessary to provide the necessary production, buffer the lack of wind and PV in-feed during absences of wind & sun and cover the in-feed prediction error. Those developments result in profitability problems of base load plants, flexible fossil-fuel plants and short-term storage facilities such as pumped storage hydro plant (PSHP)s. One possible solution for this problem is the implementation of capacity markets, where power plants are rewarded not only for energy delivery but also for providing a power capacity guarantee [4]. However, the introduction of capacity markets would add an additional subsidy mechanism, preventing an efficient market. The idea of capacity markets is thus being challenged by others, who indicate that energy-only markets can actually function efficiently for power systems with even higher RES shares [5].

### B. Consumer Perspective

Out of the many possible support schemes for RES, FIT turned out to be a highly effective option. As a result, large-scale deployment of RES, especially wind and PV has been remarkably successful. The actual FIT payments, i.e., the difference between FIT tariffs and hourly spot market prices, is financed in Germany with an additional fee on electricity consumption (*EEG Umlage*). This results in one of the highest consumer electricity price levels in Europe even though the average electricity spot price is currently one of the lowest in Europe. To prevent additional long term price increases, the consumer has the interest that the cost for FIT schemes is lowered and that the integration of RES into a competitive power market is achieved.

### C. Outline

While in the long run, subsidy schemes for RES units will eventually be phased-out, the uncertainty of RES electricity production, i.e., the inherent mismatch between production forecasts and actual production, will persist. As an intermediate step to a fully competing market setup for RES, where they face a price risk and also have to pay for the forecast error, corrections of existing power market frameworks are necessary. Such corrections have to ensure that consumer and producer perspectives are satisfied, while minimizing regulatory actions.

In this paper we analyze the following two aspects of the EPEX power market, while leaving the currently existing spot market setup intact:

1. Comparison of hourly power in-feed volume of wind/PV units to the overall load demand volume.
2. Estimation of resulting spot market price levels in case that the given wind & PV electricity volumes are settled for a range of assumed possible marginal operation costs (0 – 20 €/MWh\text{el}), see Section [IV-A] for the reasoning behind non-zero marginal costs of wind & PV units and an indicative literature review.

Based on those assumptions we will discuss the effect on the power market as well as on power plants. We will finally elude on the original question if substantial alterations to power market setups such as the introduction of capacity markets are really necessary or whether there are simpler ways to reduce market distortions in energy-only markets caused by large amounts of RES in-feed.

## II. Data

The analysis is based on high-resolution time-series data of the German power system as provided by the transparency platform of the European Energy Exchange (EEX) [6] and the European Network of Transmission System Operators for Electricity (ENTSO-E) data portal [7]. The analysis is done for the full years 2011–13. Table [I] lists the employed time-series data and data source.
Vertical grid load, wind and PV in-feed are available with 15 minute resolution, while spot prices and bid/ask curves are available with hourly resolution. All analysis with data of both resolutions are done on hourly resolutions and the 15 minute resolution data is averaged to fit hourly resolution. Vertical grid load is adjusted to match the official German total electricity supplied of 561.3 TWh in 2011 (566.7 TWh in 2012) [1], [8]. The bid/ask curve data as provided by EEX seemed to be somewhat filtered, supposedly to blur the exact bid and ask structure. The available data quality is, however, sufficient for our analysis. Daylight saving time effects have been removed appropriately from the data set.

### III. Quantitative Analysis of EPEX Spot Market

#### A. Market Volume and RES Production

The EPEX spot market is the dominant day-ahead and intra-day spot market in Central and Western Europe, directly serving Austria, France, Germany and Switzerland.

In the case of Germany, most of the spot market electricity trading is performed via EPEX. The yearly clearing volume of the electricity spot market of EPEX’s combined German/Austrian market zone amounted to around 224.6 TWh in 2011 [9]. However, this is only about 40.0% (or 35.8%) of the total electricity supplied of around 561.3 TWh in Germany (or ≈ 627.8 TWh in Germany and Austria combined) for the year 2011. By 2013, these market shares have risen to 44.2% (DE) and 39.2% (DE+AT), respectively. All of Germany’s FIT-subsidized RES generated electricity has to be traded on the EPEX spot market (DE+AT market zone). In 2011 this amounted to around 101.3 TWh or 16.8% of total electricity consumption. Out of the overall FIT-subsidized RES in-feed 18.4% came from PV and 45.1% from wind turbines [1] (and ≈ 108 TWh combined for Germany and Austria). Variable RES units thus contributed about 63.5% of all FIT-subsidized renewable electricity production. By 2013, the FIT-subsidized RES share has risen to 112 TWh (DE) and 119 TWh (DE+AT), respectively.

#### B. Time-Series Analysis

In the following, a thorough analysis of the respective yearly time-series of the EPEX cleared trading volume (German/Austrian market zone), the FIT-subsidized renewable electricity production and the final electric load demand, both for Germany only, is performed. In the remainder of this section, all result figures were calculated using hourly power in-feed and load demand time-series for the full-year 2011 (8760 hours). The results for the years 2012 and 2013 are qualitatively similar, exhibiting a steady rise of both RES energy as well spot market shares with respect to total load demand.

1) **EPEX Trading Volume versus Load Demand**: The amount of the cleared spot market volume as a function of final electricity consumption for a given hour oscillates between a minimum contribution of 23.8% and a maximum contribution of 67.9%. A histogram of the EPEX spot volume versus German total load demand volume in 2011 is shown in Fig. 3. The average ratio between cleared spot market volume and electricity demand over the course of the year was 35.8% (volume-weighted mean). It contributed thus a bit less than half, i.e., two-fifth, of all electricity demand in the German/Austrian EPEX market zone in the year 2011.

### TABLE I

| Time-Series Data          | Sources    |
|---------------------------|------------|
| Vertical grid load        | ENTSO-E    |
| German spot price         | EEX        |
| German spot bid/ask curve | EEX        |
| German wind in-feed       | EEX        |
| German PV in-feed         | EEX        |
2) **RES In-Feed versus Load Demand:** The amount of EEG FIT-subsidized RES generated electricity as a function of total electricity consumption for a given hour oscillates between a minimum contribution of 5.1% and a maximum contribution of 49.1%. The mean contribution over the full year is 15.6% (volume-weighted mean). The PV energy share of net load demand varies between zero and 22.2% with a volume-weighted mean of 3.4% (in 2011). In comparison to this, the wind energy share of net load demand varies between zero and 39.3% with a volume-weighted mean of 8.7% (in 2011).

3) **RES In-Feed versus EPEX Trading Volume:** The amount of FIT-subsidized RES generated electricity bid into the market as a function of overall cleared spot market volume for a given hour varies significantly over the course of the year. The ratio varies between a minimum of 15.3% and a maximum of 95.0%. The mean contribution of FIT-subsidized RES in-feed to the total spot market volume over the full year is 45.0% (volume-weighted mean). FIT-subsidized RES generated electricity contributes thus a bit less than half of all electricity generation that is traded in the German/Austrian EPEX market zone. A histogram of the FIT-subsidized RES in-feed volume versus the EPEX spot volume in 2011 is given in Fig. 4. The PV energy share of the spot market volume varies between zero and 47.4% with a volume-weighted mean of 8.6% (in 2011). In comparison to this, the wind energy share of the spot market volume varies between zero and 67.5% with a volume-weighted mean of 21.8% (in 2011). Other EEG in-feed, i.e., biomass, landfill and biogas as well as small hydro, make up a volume-weighted mean of ≈ 20% of total EPEX volume (in 2011).
C. Results

Although all FIT-subsidized RES generated electricity contributed less than a fifth of Germany’s and Austria’s combined total load demand (≈ 19.2 % in 2012, ≈ 20.0 % in 2013), it constituted close to half (≈ 38.7 % in 2012, ≈ 39.2 % in 2013) of the traded electricity volume of EPEX’s German/Austrian market zone. This is clearly illustrated by the gap between the histograms of both the FIT-subsidized RES in-feed volume versus total load demand and EPEX spot volume, respectively, as given in Fig. 5.

The underlying reason for the observed volatile spot price dynamics caused by the merit-order effect thus becomes obvious: The spot market is, volume-wise, largely dominated by subsidized RES in-feed, which thus drives the dynamics of the spot price clearing mechanism. This is in stark contrast to the physical situation in the German power system, in which FIT-subsidized RES in-feed plays a minor, but rising role. An obvious approach for mitigating highly fluctuating spot prices within the existing energy-only power market is thus to increase the trading volume of spot markets by incorporating more of the conventional electricity production that is currently sold bilaterally, i.e., over-the-counter (OTC), outside the EPEX spot market.

D. Comparison to Nord Pool Spot Market

Comparing the situation of the EPEX spot market to the situation in a neighboring power market, the Nord Pool Spot, reveals interesting insights. The Nord Pool is a mature multinational spot market that comprises the north and north-eastern European countries Finland, Denmark, Norway, Sweden and Estonia [10]. The yearly total load demand of the Nord Pool countries (≈ 440 TWh) is comparable in scale to the German/Austrian EPEX market zone (≈ 665 TWh) [8]. Both power markets comprise day-ahead and intra-day markets that are organized similarly. The stark contrast between the two power markets is that whereas in EPEX only around two-fifth (≈ 39% in 2013) of the yearly load demand in the German/Austrian market zone is traded on the spot market, more than four-fifth (≈ 85% in 2013) of the yearly load demand of the Nord Pool countries (except Estonia) is traded on the spot market. The evolution of the EPEX spot (EEX spot until 2009) and Nord Pool spot market shares of the yearly load demand in their respective market zones is illustrated in Fig. 6. Market shares of both spot markets have significantly grown over the years, but the Nord Pool spot market has a sizeable lead in market share over EPEX. Please note that not necessarily all of the FIT-subsidized RES in-feed in Germany and Austria (≈ 20% in 2013) may be given directly to the EPEX day-ahead spot market, i.e., as supply-side bids. Since 2010 there an obligation on German transmission system operators (TSO) to put all FIT/EEG-subsidized electricity directly onto the spot market. However, due to the increase of so-called direct marketing of RES in-feed by private acteurs, notably wind power, the data situation is not entirely transparent. Nevertheless, it is fair to assume that
all variable RES in-feed from wind & PV units, by its very nature a short term commodity, influences the spot market at least indirectly, i.e., in the form of reduced load demand bids.

To our knowledge, there exists no inherent limitation and, hence, credible reason why similar spot market shares as in the Nordic countries could not be reached also in Germany, Austria or other European countries. By doubling the EPEX spot market share, the FIT-subsidized RES in-feed share at the spot market is, logically, cut in half. Quite obviously this would lead to a significant reduction of the well-known merit-order effect of RES power in-feed. The quantitative effect of the RES in-feed share at the spot market on the merit-order effect is part of subsequent investigations in Section IV.

IV. EFFECT OF INCLUDING RES MARGINAL COSTS ON THE POWER MARKET ASK CURVE

In the following we analyze the quantitative effect on spot prices if wind and PV in-feed would have to be settled at the spot market using the marginal operation costs of RES units. The volume risk of the forecast error, i.e., predicted in-feed versus realized in-feed, has not to be covered by the RES supplier. Note, that this situation still constitutes a support scheme but a milder one than the existing FIT scheme. Compared to a fossil-fueled power plant, fuel costs of wind & PV plants or any other variable RES production units such as run-of-river hydro plants or the solar field of concentrating solar power (CSP) plants are obviously zero. There are, however, other cost components that can be considered as marginal operation costs for variable RES units. These can include marginal wear & tear from plant operation (at least the part that can be directly attributed to run-time and energy produced) for any turbine-driven plant as well as concession taxes and land-lease payments that are calculated per unit energy (in MWh_{el}) produced. Energy-based marginal concession taxes (Wasserzins, Wasserentnahmeabgabe) exist, for example, for hydro units in Vallais, Switzerland and Saxony, Germany. Land-lease payments, e.g., for the land-use of wind & PV units are at the discretion of the involved parties, i.e., land-owner and RES plant owner, but often do include a revenue component for the electricity plant.

In the mid term, e.g. by the time existing FIT-support schemes are phased-out or adapted to not include a grid in-feed guarantee, it is likely that at least a part of the spot price and volume risk of RES in-feed has to be covered by these units, notably wind & PV, directly. Such an obligation would result in a form of an insurance fee or risk coverage for the forecast error of the variable RES electricity production.
Today, system operators usually do have to cover the forecast error by acquiring control reserve power *a priori*, which will then provide the needed balancing energy in real-time.

The total marginal operation cost of running variable RES units is thus the sum of the individual cost components

\[
\text{RES marginal cost [€/MWh]} = \text{wear&tear cost [€/MWh]} + \text{land-lease cost [€/MWh]} + \text{concession tax [€/MWh]} + \text{forecast error [€/MWh]}.
\]

The effect is that the marginal operational costs for RES production, especially wind & PV units, become positive, since at least the risk coverage costs must be earned by the actual electricity production. This, obviously, will significantly change the bidding behavior of wind & PV units as well as the structure of the merit-order curve.

**A. Literature Review of Marginal Costs for Wind&PV units**

We obtained general wear&tear operation costs of RES units, essentially operation and maintenance (O&M) costs, from a literature survey of recent reports on electricity generation costs [11]–[13]. Operation cost for wind (onshore) generation were in the range of 15–27 €/MWh, whereas for PV generation costs were in the range of 22 – 33 €/MWh. Within OECD countries median O&M values of 17 €/MWh for onshore wind and of 23 €/MWh for PV have been presented [11, p. 102]. The largest share of these operation costs will not be truly marginal, i.e., in the sense that additional cost will be incurred for every addition (marginal) electricity unit (in MWh) produced. For the moving parts of wind turbines etc. one can fairly attribute some marginal O&M cost, whereas on can probably not do so in the case of PV units.

Marginal costs for land-lease as well as concession taxes will always be site-specific. For the above mentioned hydro concession taxes the cost range is about 10-20 €/MWh.

The marginal costs or insurance fee for covering the risk of forecast errors and the involved costs for calling on control reserve power and energy via ancillary service markets will also be site-specific and depend on the responsible system operator. In the case of the German TSO, the balancing cost for wind & PV forecast errors is possible due to recent regulatory transparency efforts. Here, the balancing cost has been varying in the range of 0-10 €/MWh for the years 2011-2013.

**B. Wind & PV Supply Bid Assumptions**

The subsequent analysis is based on certain assumptions regarding wind & PV marginal costs and supply bids:

- In case the FIT scheme provide a feed-in guarantee for all FIT-suported RES production: we assume that the transmission system operator (TSO) gives all RES with a large negative price bid, i.e., −3000 €/MWh to the spot market, to ensure the settlement.
- In case the FIT scheme does not provide a feed-in guarantee for all FIT-suported RES production: we assume total marginal operation costs for both wind & PV units to be in the range of 0-25 €/MWh and simulate in steps of 5 €/MWh.
- Only wind and PV are considered since they represent the majority, i.e., two-third, of German RES in-feed.
- There is no separation between on-shore and off-shore wind. Currently less than 5% of the installed wind capacity in Germany is off-shore and therefore negligible at the moment. In the future two different O&M costs for off-shore and on-shore wind power in-feed have to be considered.
- The demand side of power markets is not affected.
C. Method

Wind/PV FIT in-feed is settled over the spot market with an ask of \(-3000\ \text{€/MWh}\), since the FIT paid is independent from the achieved spot market price and the TSO has to ensure the settlement of the RES in-feed. One of the main questions is now, what would be the resulting market prices, if wind/PV would have to be settled under market conditions. In the following we investigate the impacts of settling RES in-feed with realistic marginal costs, as given in Section IV-A.

For the calculations we settle the spot market based on the EPEX bid-ask-curve. We leave the demand curve untouched and rearrange the ask curve by applying the corresponding marginal costs on wind/PV volume. The settlement is done based on the EPEX settlement [14]. Figure 7 shows the volume of the realized and the modified ask curve. Here, settling wind/PV with assumed marginal costs results in a visible jump for wind energy bids and the resulting power market ask curve.

D. Results

For the analysis, we calculate artificial spot prices under the assumption of significant non-zero marginal costs, i.e., 25€/MWh of RES in-feed for the following scenarios:

1) Wind in-feed only is settled via marginal costs.  
2) PV in-feed only is settled via marginal costs.  
3) Wind and PV in-feed are settled via marginal costs.

We discuss below the effects that the resulting artificial spot prices have on the three principal power plant types, i.e., base load, flexible peak load plants and storage units.

1) Analysis of Price Formations: First, we analyze the effect when wind in-feed is settled with marginal costs whereas PV in-feed is still subsidized. Figure 8 shows the settlement of spot prices under the assumption, that wind energy is settled with marginal costs. It is shown, that no negative price effects are existing anymore. Some hours are settled below the marginal cost of wind units. In these hours the power in-feed from other, cheaper sources is sufficient for covering the load demand; no wind power was dispatched.

Figure 9 shows the constructed spot prices where wind in-feed is still supported with FIT and PV is settled using marginal costs. The analysis shows, that the pure PV in-feed over marginal costs does not change the overall settlement of high prices above the marginal cost level. The spikes in the spot prices remain and so do negative spot price events.

Figure 10 shows the bid/ask curves using marginal costs for wind/PV power in-feed. As for wind in-feed only, some hours exist below the marginal costs of PV which are lower than the wind marginal costs. In those hours, production from other base load power plants is sufficient; no RES power was dispatched.
2) Producer Perspective: As discussed in Section I we analyze the effect of the settlement of wind/PV in-feed on three groups of power plants:

1) Base load power plants (nuclear, lignite, hard coal),
2) Peak load power plants (gas and storage plants),
3) Short term storage (PSHP and other technologies).

As shown previously in Fig. 10, all negative prices vanish as soon as RES units have to settle with their respective marginal costs. In some hours the settled spot price is even lower than the marginal cost of PV and covered by other base load plants. In addition, the marginal costs of at least some base load power plants are below the marginal cost of PV and wind units. Given those results, capacity markets for base load power plants are not necessary to make their operation profitable, if the RES in-feed is settled with their assumed marginal costs. Also all negative spot price events vanish, so the scenario where plant operators have to pay money to prevent down-ramping or plant shutdowns disappears.

The second category of plants, flexible fossil-fueled plants like natural gas fired units and larger storage plants, are not affected by the change, since they profit from peak hours.

3) Consumer Perspective: The high costs generated by the FIT will be lowered, because the RES generation can be settled at a significantly higher price. Costs for the coverage of the forecast error of wind and PV generators are still present, but determining the incurred costs due to this is clearly beyond the scope of the paper. Given the long-term guarantee of the FIT scheme (20 years), the overall RES
deployment cost can be lowered significantly and a transition to a competitive market seems possible.

4) RES Producer Perspective under Market Constraints: As shown in Fig. 7 and 10, a large amount of RES in-feed is still settled over the spot market, if RES in-feed is given to the market with marginal costs. While during the FIT period, only the costs for FIT will be lowered, a real market situation, independent from the prediction error, seems also possible. Future work will address the impact of such a regime change, which gives no RES in-feed guarantee, for the effective RES grid integration.

E. Sensitivity Analysis of Marginal Operation Costs

Since the real marginal costs of wind & PV are site-specific and thus hard to estimate, we have compiled a sensitivity analysis of the impacts of different assumed marginal operation costs, ranging from 0 – 20 €/MWh in steps of 5 €/MWh, for either wind or PV power in-feed.

The effects of these assumed marginal costs on the spot market clearing are illustrated in Fig. 11–12. A quantitative analysis of average spot prices and their volatility is given in Tab. II–V. While the effects increase with higher marginal costs, the overall observations of the paper are backed up. As can be seen, average spot market prices will be higher if wind or PV in-feed are bid into the spot market with positive marginal costs. Also, the volatility (standard deviation) is decreasing. Both effects are significantly more pronounced in the case of wind power in-feed. Figure 12 clearly shows that positive marginal costs for
Fig. 12. Comparison of realized spot with FIT and spot with different marginal costs (0 – 20€/MWh) (only current wind in-feed). Wind in-feed push the spot clearing prices above zero in all instances (not the case for PV in-feed). The original clearing results for an in-feed guarantee via highly negative bids (−3000 €/MWh) are also shown.

| Marginal cost (PV) | 2011 | 2012 | 2013 |
|-------------------|------|------|------|
| -3000             | 51.5 | 42.8 | 37.9 |
| 5                 | 51.55| 42.8 | 38.0 |
| 10                | 51.6 | 42.8 | 38.0 |
| 15                | 51.6 | 42.8 | 38.1 |
| 20                | 51.6 | 42.9 | 38.3 |

**TABLE III**

| Marginal cost (PV) | 2011 | 2012 | 2013 |
|-------------------|------|------|------|
| -3000             | 13.4 | 18.6 | 16.5 |
| 5                 | 13.4 | 18.6 | 16.2 |
| 10                | 13.3 | 18.6 | 16.2 |
| 15                | 13.3 | 18.6 | 16.0 |
| 20                | 13.3 | 18.5 | 15.8 |

**TABLE IV**

| Marginal cost (wind) | 2011 | 2012 | 2013 |
|----------------------|------|------|------|
| -3000                | 51.5 | 42.8 | 37.9 |
| 5                    | 51.6 | 43.2 | 38.0 |
| 10                   | 51.6 | 43.3 | 38.1 |
| 15                   | 51.7 | 43.4 | 38.5 |
| 20                   | 51.8 | 43.6 | 38.9 |
TABLE V
STANDARD DEVIATION OF SPOT PRICE (MARGINAL COSTS FOR WIND IN-FEED ONLY)

| Marginal cost (wind) | 2011 | 2012 | 2013 |
|----------------------|------|------|------|
| -3000                | 13.4 | 18.6 | 16.5 |
| 5                    | 13.3 | 15.8 | 15.9 |
| 10                   | 13.2 | 15.7 | 15.7 |
| 15                   | 13.0 | 15.5 | 15.2 |
| 20                   | 12.7 | 15.0 | 14.5 |

V. CONCLUSION

While feed-in tariff (FIT)-subsidized renewable energy sources (RES) generated electricity contributed less than a fifth of Germany’s total load demand, it represents almost half of the traded spot volume. This is no surprise as the European Power Exchange (EPEX) spot market only has a market share of about two-fifth of Germany’s total load demand in recent years (2011-2013). The spot market is therefore largely dominated by subsidized RES in-feed, which in turn drives the dynamics of the spot price clearing mechanism. The well-known merit-order effect, i.e., falling spot price levels as well as highly fluctuating spot prices, is thus amplified to a level that is in clear contrast with the physical situation in the German power system, in which RES in-feed still plays a minor, albeit rapidly rising role.

An obvious approach for mitigating the merit-order effect within the existing energy-only power market, i.e., without changing the market mechanism towards a capacity market or else, is to increase the spot markets trading volume to actually capture the majority of the load demand. This can be achieved by incorporating more of the electricity production that is currently sold bilaterally, i.e., over-the-counter (OTC), outside of the spot market. Comparably mature power markets like Nord Pool Spot in the Nordic countries achieve a market share of four-fifth of the respective total load demand. Reducing the dominance of RES in-feed in EPEX by increasing its market share will significantly alleviate the merit-order effect.

We also show that the settlement of RES at the spot market with marginal cost is possible. Negative prices disappear and in most days, at least some of the RES production volume is settled. Base load power plants profit from the situation because of an elevated average spot price level. Gas-fired power plants and hydro storage units covering peak hours are not effected, since peak prices are not effected by the above discussed changes. Because of the further decreasing peak-base spread, the already non-profitable short term storage plants suffer even more. Given base load power plants that have sufficient operational flexibility in terms of fast ramping, start/stop times and minimum operation point requirements, energy-only markets seem to work even for high RES penetration scenarios.

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