Statistical Analysis of the German Electricity Market in Presence of Renewables

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Abstract—Increasing penetration of variable renewables has several impacts such as lower market prices, higher generation variability and higher generation forecast error. This paper provides a statistical analysis over the above-mentioned impacts of variable renewables on the German electricity market. Results show that the correlation between price and residual load is much higher than the correlation between price and RES generation. Besides, a higher portion of volatility comes from load rather than RES generation. However, the variation in the load is not a big problem since the load can be very well predicted, while the forecast error of RES generation is relatively high. Day-ahead forecast error of variable RES in the German market with 20% share of RES has a normal probability distribution with mean value of 0.3% and a standard deviation of 2.2%. Also, results show that higher RES generation volatility does not necessarily lead to the higher price variations.

Index Terms—Day-ahead Price, Electricity Market, Generation Forecast Error, Renewables, Statistical Analysis

I. INTRODUCTION
Electricity generation from renewable energy sources (RES) is rapidly increasing due to generous support schemes in most of the European countries. Specifically, the growth of generation from variable RES such as wind and solar is significant. The rapid growth of variable RES share in electricity generation has major impacts on electricity markets. The authors in [1] summarize the historical development of electricity generation by renewables in European countries, main renewable electricity support schemes in Europe and the effectiveness and efficiency of different promotion policies. The main conclusion is that promotion strategies, regardless of the type of support instrument, must persist for a specified planning horizon. A comparison of the effectiveness of different renewable support policies in several electricity markets is presented in [2] and [3]. The research by [4] identifies the required modifications in the current trends of energy consumption and energy efficiency in order to achieve a more sustainable energy system.

The integration of large amounts of renewables into the electricity market is a driver which exasperates the resource adequacy problem [5]. The authors in [6] discusses that increasing renewable penetration makes an impact on the long-term resource adequacy by reducing the average market prices and increasing the price spread. The increasing share of renewables with very low marginal cost leads to the merit order effect which denotes the rightward shift of conventional generators in the supply curve and three related effects can be observed in [7], [8] and [9]. The first effect is the reduction in the utilization of all conventional generators. The profitability reduction of the peak and medium-load power plants is relatively stronger through a significant reduction of both their utilization time and generated electricity. The second effect is the reduction of both the average electricity prices and the frequency of scarcity prices. This effect leads to a significant reduction of inframarginal rent for all generators. As the base and medium-load generators have higher investment costs, they are more vulnerable to the lower prices. A permanent lack of these inframarginal rents lowers the investment incentives and endanger generation adequacy in the long run. The third effect is that the dominance of variable renewables' generation increases the variability of generation profile.

Figure 1 illustrates that the increasing share of variable renewables leads to the rightward shift of the supply curve which is called as the merit order effect. This effect occurs due to the fact that renewables have near-zero marginal cost and they are placed on the left side of supply curve before all of conventional generators. As the right-hand side of Figure 1 shows, the merit order effect of renewables results lower market prices at the same demand level. The lower market prices affect on the profitability of both renewable and conventional generators. The capital intensive generators such nuclear power plants would be more influenced by low market prices. As a result, all conventional generators would encounter difficulties to be able to recover their fixed costs and might require support policies. Another impact of merit
order effect is that peak-load generators such as gas-fired power plants are operating during a few hours of very high demand period (see Figure 1.). Besides, the utilization time of other conventional generators such as coal would be decreased.

![Merit order effect of increasing renewables penetration](image)

The increasing penetration of renewables results a considerable reduction in the utilization of all conventional generators. However, the impact of renewables on the utilization of peak load and medium load generators is relatively stronger due to the significant reduction in their load factor. By increasing the share of renewables, these generators will lose higher amount of their share in generation profile which leads to significant reduction in the short-term and long-term profitability of them.

This paper is organized as follows: In section II, an introduction to the German electricity market is presented. A statistical analysis of the impact of renewables on the German market is performed and the results are discussed in section III. The main conclusion of this study is provided in section IV.

II. GERMAN ELECTRICITY MARKET

The German electricity market has been faced with growing volumes of investment in renewable energy sources (RES) in the recent years. Therefore, the case of this market seems suitable for examining the impact of RES on various market parameters. In order to provide an overview of the German electricity market, a data set including hourly actual and day-ahead forecasts of renewable generation, hourly load values as well as hourly day-ahead prices in Germany are investigated. In this section the term "renewables" refer to variable renewables such as wind and Photovoltaics (PV). Such delimitation is justified by the fact that the main challenges in the German electricity market such as generation and price volatility, high generation forecast errors, and negative prices are mostly a result of increasing shares of variable RES.

Most of renewable generation in Germany is traded at the day-ahead market. At the European Power Exchange (EPEX), which hosts day-ahead auctions for the German market, hourly prices for each day are determined through a uniform price auction held on the previous day. Suppliers of RES bid their forecasted generation quantities for the next day into the auction and the difference between the actual and forecasted renewable generation volumes is traded at the intra-day market.

The data set which is used to perform this analysis includes hourly electricity generation by different generation technologies, hourly day-ahead forecasts of renewable generation, hourly load values, hourly day-ahead market prices, and forced outage period of conventional generators in 2012 and 2013.

III. DESCRIPTIVE STATISTICS OF RENEWABLES IMPACT ON MARKET

In this part, a statistical analysis of the German electricity market using generation, load and market price data is performed and the results of the analysis are discussed. The performed analysis includes the evaluation of renewables impact on market prices, variability of renewables and the forecast error of renewable generation.

A. Market Price

In the day-ahead market auction, the quantity bid by renewable generators is equal to the day-ahead forecast of their generation. Therefore, in order to investigate the effects of renewable generation on the price, a correlation between hourly day-ahead forecasts of wind and PV generation and hourly day-ahead market prices is analyzed. In Figure 2, the scatter plot represents the variation of renewable generation versus day-ahead market prices. Results show that by increasing renewable in-feed to the market, the market price decreases. The analysis of day-ahead market prices in Germany shows that there were 39 hours with negative day-ahead prices in 2012. Almost all of these negative prices occurred between 12 a.m. to 8 a.m. between December, 25 and January, 5, a period in which electricity load is quite low. On the other hand, almost all price spikes in the German market occurred during February and December on the days when electricity consumption is very high due to cold weather conditions.

![Renewable generation and day-ahead market price variations in Germany in 2012](image)
The scatter plot of residual load with respect to the market prices is depicted in Figure 3. Residual load is calculated by subtracting hourly renewable generation values from hourly load values. This figure shows that residual load and price are highly correlated and increasing residual load results in higher market prices. The slope of the price variation curve is relatively steep during periods of high residual load, which means that prices tend to increase rapidly when either gas-fired power plants or emergency operating reserves become marginal producers in the market. Results show that negative prices occur when residual load is low. A low residual load may occur in the event of low electricity demand, high volumes of electricity generation from RES or the combination of the two. Similarly, high price spikes occur during high residual load events, which may result from a very high load, low volumes of generation from RES or the combination of the two. This plot can thus be interpreted as a merit order curve of conventional generators at the day-ahead electricity market.

Figure 3. Residual load and day-ahead market price variations in Germany in 2012

B. Variability of RES Generation

The Electricity generation from variable RES such as PV and wind differs from conventional generation in many ways. Electricity generation from solar energy and wind is highly dependent on specific weather conditions such as wind speed, air density, solar irradiation, cloud cover, and temperature. High variability of renewable generation in electricity markets with large shares of RES could lead to several issues potentially affecting power system operation and planning. This section provides descriptive statistics of the variability of wind and PV generation and the variability in residual load. Hourly variability of each parameter is equal to the hourly gradient of that parameter. The minimum, maximum, mean absolute, and standard deviation of hourly variation of renewable generation and load is presented in Table I.

The installed capacity of wind and PV generation in Germany in 2012 amounted to 31,332 and 33,033 MW. Taking into account the capacity factor of 12 % for wind generation and 9 % for PV generation, the average hourly generation from variable RES would equal 6732 MWh. The table shows that the maximum and minimum hourly renewable generation gradients are +5.91 / -5.34 GW. The ratio of the maximum and minimum renewable generation gradient to the average hourly renewable generation is +88 % and -80 %, respectively. Results show that the average hourly gradient of renewable generation is approximately 1 GW and the ratio of average gradient of renewable generation gradient to the average renewable generation is 15%. These findings prove that the variability of RES generation in the German electricity market is high. By increasing the share of variable RES, the market will consequently face a higher level of variability of the generation profile.

<table>
<thead>
<tr>
<th></th>
<th>Max/Min (GW)</th>
<th>Mean (GW)</th>
<th>St. deviation (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Gen.</td>
<td>+3.0 / -2.1</td>
<td>0.27</td>
<td>0.38</td>
</tr>
<tr>
<td>PV Gen.</td>
<td>+5.2 / -4.8</td>
<td>1.39</td>
<td></td>
</tr>
<tr>
<td>Wind+PV Gen.</td>
<td>+5.9 / -5.4</td>
<td>0.99</td>
<td>1.49</td>
</tr>
<tr>
<td>Load</td>
<td>+10.5 / -6.2</td>
<td>2.06</td>
<td>2.70</td>
</tr>
<tr>
<td>Residual Load</td>
<td>+10.9 / -7.1</td>
<td>2.06</td>
<td>2.68</td>
</tr>
</tbody>
</table>

A histogram of hourly variation in electricity generation from solar and wind energy in Germany in 2012 is depicted in the top plot in Figure 4. The histogram for the percentage of the variation in RES generation is depicted in the bottom plot. The percentage of variation in renewable generation lies in the range from 0 % to 250 % of hourly renewable generation and the mean value is equal to 17 %. It could be interpreted in a way that hourly variable RES generation varies on average in the range of 17 %. Increasing the share of RES in the electricity market will result in more variability of the generation profile. Therefore, an adequate volume of flexible generation capacity is required in electricity markets with high shares of RES in order to provide a rapid response to the high variability levels of renewable generation fleet. Besides, balancing markets will play an important role in providing the required short-term flexibility in order to compensate the
uncertainties and stochasticity of generation from variable RES.

Figure 5. Hourly variation of renewable generation versus price variation in Germany in 2012

Hourly variation of renewable generation versus hourly price variation is depicted in Figure 5. The outliers both in case of price variability and in case of renewable generation variability are excluded from the data set. Results show that during the low variability of RES generation, price spread is relatively high. By increasing the variability of renewable generation, market price spread decreases. According to the initial expectation, higher volatility in renewable generation would result in higher price variations, however, the results proved the opposite. The reason for this lies in the fact that price variability depends on several factors such as hourly electricity load, load variations, available generation from different generators and the share of RES in the generation mix. Therefore, price variability must be analyzed by considering all related factors.

C. RES Generation Forecast Error

Day-ahead forecasts of renewable generation are essential to determining the price at the day-ahead market auction. Here grid operators provide renewable generation forecasts for the next day with hourly resolution. The difference between real and forecasted renewable generation is traded at the intra-day market. More precise forecasting of renewable generation is a key factor to facilitating further integration of RES in the future. The renewable generation forecast error is defined as a difference between forecasted values and the actual values. The histogram of the wind and PV day-ahead forecast error in the German electricity market is shown in Figure 6. According to the upper plot, the day-ahead forecast error for renewable generation lies in the range between -7 GWh and 8 GWh. The renewable generation forecast error has a normal distribution with the mean value of -1.70 MWh and the standard variation of 1200 MWh. The lower plot shows the histogram of forecast error values as a percentage of hourly load which has a normal distribution with the mean value of -0.3 % and the standard variation of 2.2 %. Results show that the forecast error of renewable generation is relatively high. By increasing the share of variable RES in the market, the volume of the forecast error will increase, which could lead to inefficiency and high operation cost for electricity system. Hence, besides improved forecasting techniques, adequate volume of flexible generation at the intra-day market is required to offset the forecast error of renewable generation.

Figure 6. Day-ahead forecast error of wind and PV generation in Germany in 2012

IV. CONCLUSION

The integration of the large share of variable renewables into the electricity markets brings up some challenges in the electricity system. This paper aims to analyze three main impacts of increasing renewable penetration, including a) reducing average market prices b) increasing the variability of generation profile and c) reducing the predictability of generation. This paper provides the descriptive statistics of above mentioned impacts of RES in the German electricity market. The results reveal some interesting facts about the effects of RES in that market. All price spikes have occurred when the residual load is high and all negative prices have occurred during the Christmas holidays and national holidays mainly due to the low demand. Besides increasing RES feed leads to lower electricity prices. However, the correlation between price and residual load is much higher than the correlation between price and RES generation.

In the presence of 20% share of RES in the German market, the average hourly variation in RES generation is 0.99 GW, while the average hourly variation in load is 2.06 GW. It shows that a higher portion of volatility comes from load rather than RES generation. However, the variations in the load is not a big problem since the load can be very well predicted, while the renewable generation forecast error is relatively high. Day-ahead forecast error of variable RES in the German market with 20 % share of RES has a mean value of 0.3 % and a standard deviation of 2.2 %. Higher share of RES will result in an even higher forecast error and adequate volume of flexibility in the generation and demand side is
required to offset the variability and forecast error of RES generation.

Besides, on the contrary to the general expectations, higher variation in RES generation does not necessarily result in higher price volatility. The reason for this lies in the fact that price variability depends not only on the RES generation volatility, but also on hourly electricity load, load variations, available generation from different generators and the share of RES in the generation mix.

REFERENCES


