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Understanding distribution grid congestion caused by electricity generation from renewables

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Abstract. Worldwide the increasing amount of electricity from renewable energy sources (RES-E) is challenging the way how electricity systems traditionally work. While conventional power plants used to be located close to major demand centers, a great share of the RES-E capacity installed over the last years is located far away from areas of high demand. In various countries with a strong growth of RES-E this causes an increasing amount of grid congestion both on the transmission and distribution level, for example in Germany.

In this work we analyze congestion events in the distribution grid caused by RES-E feed-in and the resulting curtailment. The analysis is applied to an exemplary distribution grid in Northern Germany which faces frequent curtailment. We characterize observed curtailment events with regard to extent, length and frequency and illustrate the importance of location within the grid. The results are relevant for research on how to decrease curtailment and thus increase RES-E utilization within the distribution grid. Our goal is to provide detailed insights on the occurrence of RES-E curtailment to enable research on how to allocate a more efficient dispatch within congested grid areas and on technologies that can contribute to alleviating congestion.

Keywords: Distribution grid · congestion management · renewable energy

1 Introduction

The continuous expansion of renewable energy in the German electricity sector leads to an increasingly decentralized generation portfolio, requiring far-reaching adaptions to the transmission and distribution grids. However, the grid does not expand as fast as the renewable distributed generation capacity (DG), resulting in DG-curtailment due to grid congestion [6, 8, 9, 12]. Despite the German Renewable Energy Act, which requires conventional generation capacity to shut down first during congestion, the curtailment of DG increased tremendously over recent years (Fig. 1). As a consequence, an increasing amount of potentially generated electricity from renewable energy sources (RES-E), a clean resource and basically free of marginal costs when wind and photovoltaics are concerned, remains unused.

Fig. 1 shows the ongoing trend of increasing curtailment of RES-E over the recent years. In 2014 alone, the same amount of energy was curtailed as it had been during the years 2009 through 2013 in aggregation. This trend is continuing in 2015, as curtailment in the first three quarters of the year has already exceeded 2014's total value. The majority of curtailment concerns wind onshore power plants (85%), followed by photovoltaic (9%) and biomass plants (6%), averaged over the curtailment in 2009 through the third quarter 2015. Almost the entire sum of curtailed energy is evoked by activities on the distribution grid level, where most of the installed capacity of RES-E is connected to the grid. The most recent report on curtailment by the German Federal Network Agency splits the entity of curtailed energy by 92,2% to the distribution grid and 7,8% to the transmission grid [10].

The Federal Network Agency has acknowledged recent developments by increasing the frequency of their monitoring reports on grid and system stabilizing measures from a yearly to a quarterly basis. Even though these public figures are vital to get an overall understanding of the current development, quarterly figures per federal state, are insufficient for in-depth analyses. In order to investigate congestion events and develop solutions for improving congestion management measures, researchers require detailed information about occurring congestion events and resulting amounts of curtailment in a high temporal and geographical resolution.

Two reports on behalf of the Ministry of Energy, Agriculture, the Environment and Rural Areas in Schleswig-Holstein and on behalf of the German Federal Ministry for Economic Affairs and Energy, published in December 2012 and July 2014, conducted more detailed analyses of curtailment activities [7, 12]. By comparing up to three different approaches, both papers emphasize the importance of a suitable method to avoid high over- or underestimations when analyzing curtailment. Furthermore, the analyses of these papers show that several databases have to be combined to allow more detailed analyses including a high temporal and spatial resolution. [6, 7, 11, 12]

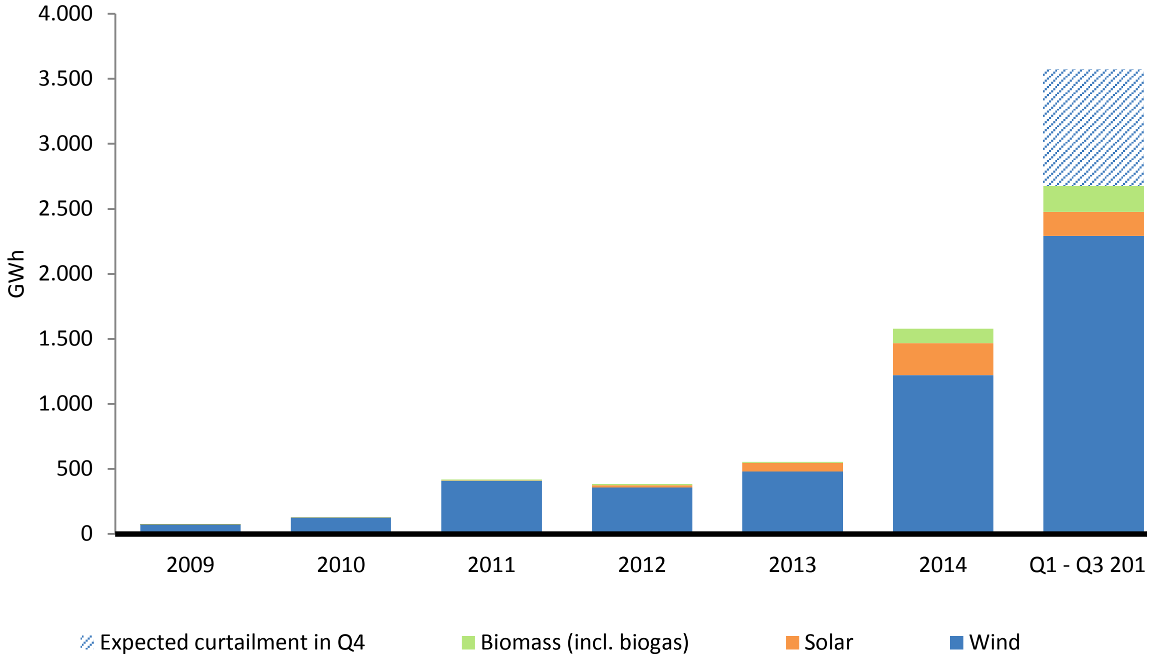

Fig. 1. Development of curtailed energy between 2009 and 2015 in Germany [GWh] [8–10][1]

The strong increase of curtailed renewable energy urges for a better understanding of this development in order to develop effective counter-measures. Considering both, the steep increase in 2014 and 2015 as well as the limited temporal and spatial resolution of data in available publications, additional research on this topic is essential. Based on recent research on modelling techniques for distribution grids at the Chair of Energy Economics, Institute for Industrial Production, KIT [13] this paper analyzes a concrete distribution grid covering the federal state Schleswig-Holstein (SH). The amount of curtailed energy in this grid area accounts for roughly half of the total curtailed energy in Germany [12].

In order to develop an in-depth understanding of grid congestions and curtailment measures, a temporally and spatially high-resolved database is essential. This allows the disaggregated characterization of the spatial distribution as well as of the frequency and duration of curtailment events. However, currently available data sources cannot fulfill these requirements.

Filling this gap, the proposed method in this paper combines various databases in order to overcome the lack of highly disaggregated data and conducts an in-depth analysis on curtailment activities. The insights provided by the application to the high voltage distribution grid of SH in this work can support the planning of effective grid expansion measures as well as the development and implementation of more cost-efficient alternatives like demand side management or the coupling of the power and heat market.

2 Methodology and Data

The goal of this paper is the analysis of curtailment activities caused by grid congestions in the considered distribution grid with a high temporal and spatial resolution. In the given case, a high temporal resolution is defined as one-minute intervals. Considering the network structure of a power grid, a spatial disaggregation on the substation level of the underlying electricity grid seems appropriate. Having generated a high resolved database on grid congestion events, the data set can not only be used in order to characterize curtailment activities from a holistic

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[1] At the time of writing the curtailment of quarters one through three of 2015 were published. The dashed form approximates our expected curtailment in quarter four (Q4) of 2015.

perspective, but also to analyze specific regions over the course of the last years in detail. Due to the large portion of wind energy among the amount of total curtailed energy of roughly 90% [12], our approach focusses on wind power and neglects curtailment from other RES-E.

The computation of this high resolution database requires the consolidation of several data sources (Fig. 2). Firstly, information about historic curtailment events is essential. Grid operators are obliged to publish information about their feed-in management activities. Looking at the distribution grid level, the quality of available data on curtailment events has significantly improved since 2014: The spatial resolution has increased from substation-level to DG plant-level stating the time interval and reduction level for each curtailment event on a one-minute temporal resolution.

Secondly, detailed plant data is necessary to conclude from the curtailment event data to the spatial distribution and the extent of curtailed energy. Plant data includes geo information, commissioning date and nominal power of all wind power plants in SH.

Finally, the spatial structure of the underlying high voltage distribution grid is crucial in order to match published curtailment events on substation level with affected wind power plants and vice versa. The grid infrastructure was approximated from the overpass-turbo interface [3] which relies on data from the OpenStreetMap project.

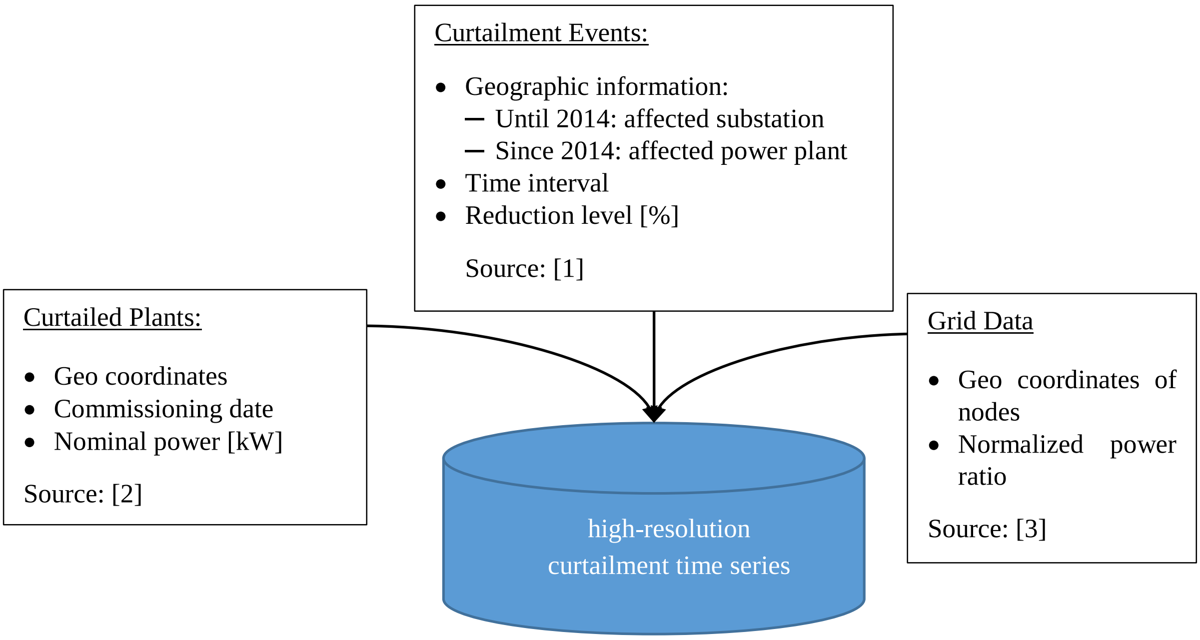

Fig. 2. Consolidation of different data sources to generate high resolution database (own diagram)

The result of the data consolidation is a database consisting of a grid-node specific time series quantifying curtailed energy on a one-minute resolution. In the following, we describe how the one-minute curtailment signals from single wind turbines are aggregated on a substation level and for the whole distribution grid modelled in this work.

2.1 Allocation of wind power plants to distribution grid nodes

In order to aggregate curtailment on a grid node level, we need to know the individual unit's connection to the grid. Since no information is available about where single wind power plants (WPP) are connected to the grid, a heuristic approach based on the location of plants and grid nodes is applied: We assume that WPP are connected to the nearest grid node (Fig. 3). In cases there are several nodes within a plant's vicinity, we only take those into account that do have curtailment events in their record.

In our analyses, a single curtailment event is defined as the action of reducing the maximum feed-in of an arbitrary number of wind plants at a single grid node for an arbitrary duration to a level strictly smaller than 100%. Acknowledging the uncertainty from the above mentioned heuristic approach for the allocation of WPP to grid nodes, we rule out grid nodes that contribute less than 0.1% of the total curtailed energy per year for the computation of the key figures below. Therefore, curtailment events, caused by a single plant allocated to the wrong node, are filtered out.

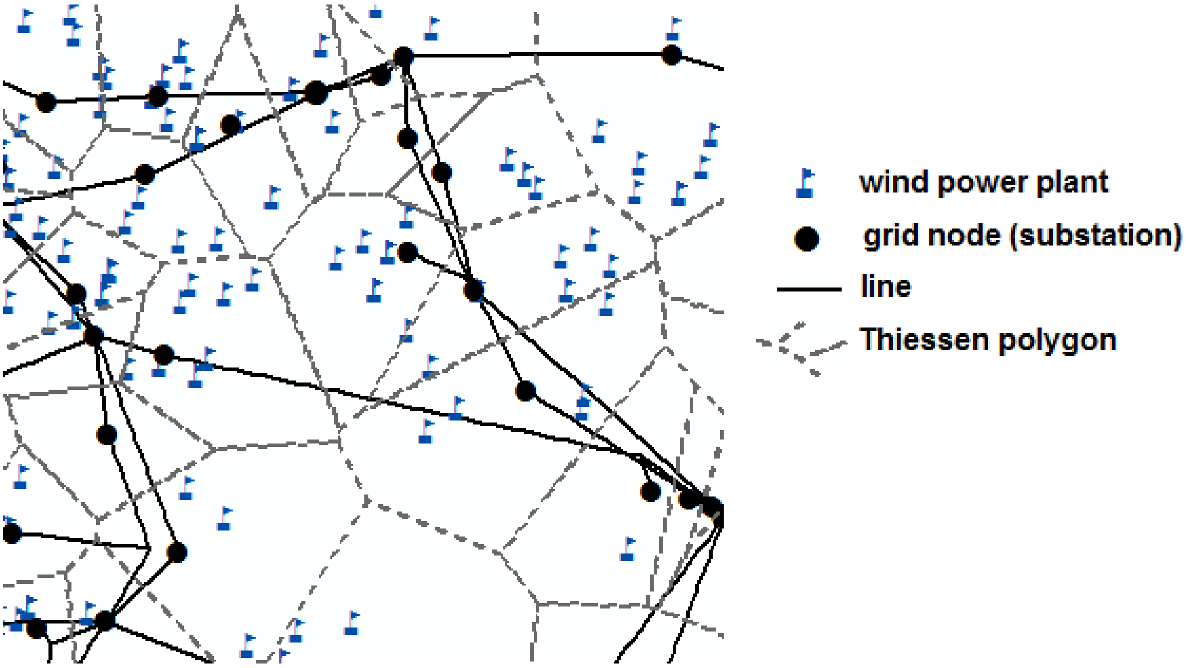

Fig. 3. Illustrative grid structure and spatial distribution of wind power plants in SH (own diagram)

2.2 Calculation of curtailment on a nodal basis

The available publications about curtailment name only the affected plant and duration of the curtailment and not the amount of curtailed energy. In order to calculate the curtailed energy, it requires the potential electricity generation of each plant during curtailment, as if there was no curtailment. A very simple approach would be to use the rated turbine capacity as proxy for the generation potential during curtailment events. However, it can be considered very unlikely for all WPP to be generating at nominal power at the same time, even during times of curtailment when high wind speeds occur. The power duration curve of any wind power portfolio tends to change with increasing portfolio size in such a way that high capacity factors become less likely (Fig. 4).

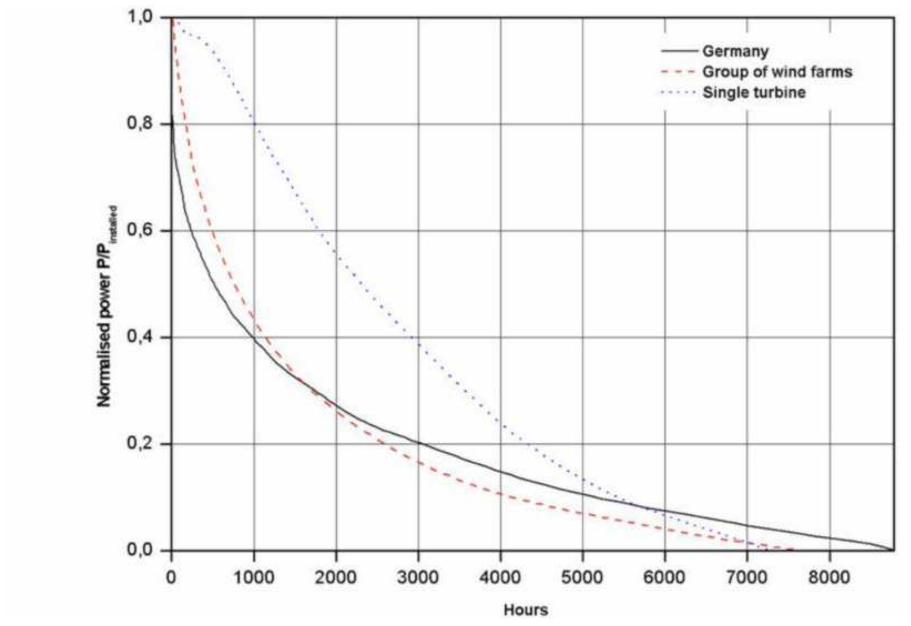

Fig. 4. Schematic power duration curve of a spatial distributed wind power plant portfolio [4]

Therefore, we apply a hypothetical feed-in-level during curtailment below the rated turbine capacity in the following. We assume that curtailment activities take place during hours with the highest generation level of WPP. To quantify the potential power generation during those hours, we employ the concept of the maximum amplitude of renewable supply (MARS) (compare [14]):

$$MARS_{\alpha} = \frac{1}{(N-t)} \sum_{t}^{N} x_t$$
$$|\left[x_1 \ \leq x_2 \ \leq \cdots \leq x_t \ \leq \cdots \leq x_N \right]; t = max\left\{k \in \mathbb{N} | k \leq \frac{\alpha}{100} N\right\}; \alpha < 100 \qquad (1)$$

$x_1 \ \ldots x_N$ denote the elements of a curtailment-event time series and N the number of elements within the time series. The α-quantile is defined as the ratio of time steps with curtailment to the total number of time steps.

The subsequent calculation of the MARS requires the wind generation time series of the analyzed wind portfolio. This data is not available for the grid area of SH-Netz. However, it is available for the wind portfolio within each of the four German transmission grid operators. We choose the WPP portfolio of the transmission grid operator Tennet, which is the transmission grid operator covering SH. The area covered of Tennet's grid is significantly larger than SH and the wind portfolio has a much greater capacity (12.288MW [2] vs. 3.373MW [5] in 2012), but no better data of a more similar WPP portfolio are available to us. Hence, the hereby calculated MARS should be regarded as a rough approximation.

The resulting equation to compute the curtailed energy $W_{n,t}$ is shown in (2). It incorporates the reduction level $L_{n,t}$ at node n and time step t, the nominal power $P_{max,I}$ of the respective WPP as well as $MARS_{norm}$ which is the MARS normalized by the aggregated rated capacity of the underlying WPP-portfolio.

$$W_{n,t} = \sum_{i=1}^{k_n} \left(1 - L_{n,t}\right) * MARS_{norm} * \frac{P_{max,i}}{60} * d \qquad (2)$$

$W_{n,t}$:	curtailed energy [kWh] at node n and during minute t
$L_{n,t}$:	reduction level at node n and minute t $\left(0 \leq L_{n,t} \leq 1\right)$, e.g. "feed-in less than 30% of $P_{max,i}$"
$MARS_{norm}$	MARS normalized by the rated capacity of the underlying WPP portfolio [-]
$P_{max,i}$:	rated capacity of wind power plant i [MW]
k_n:	number of wind power plants connected at node n
d:	duration of the time steps in minutes [1min]

3 Results

By applying the above explained method to the introduced data sources, time series with a high temporal and spatial resolution representing the historic curtailment events in SH are generated. This chapter summarizes these results, presenting insights on the characteristics of renewable curtailment in a German distribution grid.

One key result of this paper is the spatial representation of curtailment events. Table 1 summarizes the main findings on the temporal characteristics of curtailment events. The results clearly show an upward trend in renewable curtailment during the years 2012 till 2015. The number of curtailment events has almost increased by 400% from 2012 to 2015 while the number of affected nodes has more than tripled. Therefore, not only more nodes are affected, but also the average number of events per node has increased. At the same time the average duration of a single curtailment event has risen from less than two hours to 14.6 hours.

Table 1. Key figures of curtailment events at wind power plants in the grid of SH-Netz between 2012 and 2015 (based on model input introduced in section 2)

Key Figures	**Unit**	**2012**	**2013**	**2014**	**2015**
Curtailment events	#	1.039	433	2,500	4,258
Affected nodes	#	12	10	41	43
Summarized duration of curtailment events	[h/a]	1.761	1.101	20.901	62.047
Average duration per curtailment event	[h]	1,7	2,5	8,4	14,6
Average total duration per year at affected nodes	[h/a]	147	110	510	1.443
Maximum total duration per year at affected nodes	[h/a]	561	341	1.780	4.335

Fig. 5 shows the frequency distribution of the duration of curtailment events for the years 2014 and 2015. In 2014, almost a third of the curtailment events had been shorter than two hours while more than 80 % of all events are in the time interval with a maximum of 12 hours. Less than 10 % of the events lasted for longer than a whole day. In 2015, the share of events that were shorter than two hours decreased to 22 % while almost a third of the events were longer than 12 hours. In addition, the number of curtailment events that lasted longer than a day increased significantly.

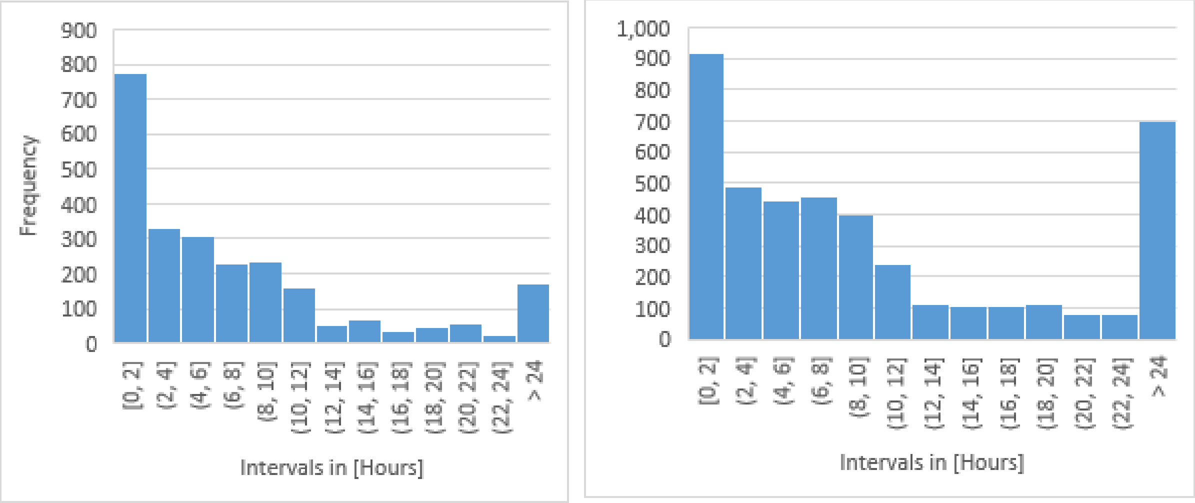

Fig. 5. Frequency distribution of the duration of curtailment events for the year 2014 on the left and 2015 on the right (own calculation)

The results of the evaluations summarized in Table 1 and Fig. 5 identify two significant drivers of the observed, steep increase in curtailed energy presented in Fig. 1: Both the total number of curtailment events and the duration of the events are growing over time.

While Table 1 represents different metrics to characterize the duration of curtailment events, Table 2 summarizes the amount of curtailed energy resulting from the computations and gives reference values for validation. In the first scenario “High”, the curtailed energy is computed based on the nominal power for all curtailment events. This scenario overestimates the reference values in two out of 4 scenarios. For 2013 and 2014, the scenario reaches less curtailment than reported and for 2012 it almost reaches the published level, despite assuming that all WPP would run at rated capacity during all curtailment events in this scenario. This is a surprising result and suggests that either the published data on curtailment events for the years 2012-2014 miss quite a few of curtailment events or the published sum of curtailment for those years is flawed. The “High” scenario overestimates the curtailment for 2015 as expected.

The second scenario “Realistic” uses the MARS based on the power duration curve of the Tennet WPP-portfolio (application of Tennet WPP portfolio discussed above in section 2). While applying the MARS increases the difference between calculated and published yearly curtailment-sums in 2012-2014, it yields a tremendous improvement for 2015. As expected, the MARS based on the Tennet portfolio is smaller than the fitted MARS for SH, which was calculated in such a way that applying it would yield exactly the published values. This does not come as a surprise, since the much greater wind portfolio in the Tennet region produces far less extreme values compared to a smaller portfolio or even single wind parks (compare Fig. 4). Hence, the MARS based on a large wind portfolio tends to be smaller than a MARS based on a small wind portfolio. This is confirmed by the underestimation of our results presented in Table 2. While the fitted MARS in 2015 of 0,56 appears to be in a realistic magnitude, values greater than the Tennet-based MARS or even greater than 1 suggest missing or wrong data input.

Table 2. Calculation of curtailed energy based on the normalized power ratio (own calculation)

		2012	**2013**	**2014**	**2015**
Reference value [10, 12]	[GWh]	262	239	1.092	2.418[2]
Average share of hours with curtailment per year at affected nodes (α)	[-]	2%	1%	6%	16%
Maximum amplitude of renewable supply ($MARS_{\alpha}$) – applied to *Tennet* portfolio	[MW]	8.647	9.636	9.240	10.055
Average rated capacity of *Tennet* portfolio [2]	[MW]	11.762	12.991	15.649	20.787[3]
Scenario “**High**”: Curtailment at nominal power	[GWh]	275	158	989	4.337
Normalized MARS	[-]	0,74	0,74	0,59	0,48
Scenario “**Realistic**”: Curtailed energy based on normalized MARS	[GWh]	204	117	584	2.082
Fitted MARS (to match reference value)	[-]	0,95	1,51	1,10	0,56

While applying the fitted MARS would lead to the yearly sum of the calculated time series to match the published values, it would also distort the amplitude of events. The following assessment of results is based on the curtailment time series applying the normalized MARS of the “Realistic” scenario and not the fitted MARS. We presume the missing curtailed energy to stem from unreported curtailment events rather than a higher generation level expressed through the fitted MARS. This poses an important assumption when regarding the results.

A helpful representation of time series data for energy systems analysts is the power duration curve or curtailment duration curve in this case (Fig. 6). Comparing the depicted curves for the years 2012 to 2015, two trends become obvious:

- The number of hours per year during which curtailment activities take place are strongly increasing. The number of affected hours rises from roughly 1,000 hours per year in 2012 and 2013 to more than 4,000 hours in 2015.
- Simultaneously, the average curtailed energy per hour has significantly increased. In 2015, curtailment events with up to 1,400 MW of curtailment occur.

These insights are valuable when developing alternative applications for excess power in case of grid congestions. Power-to-gas and power-to-heat technologies can use excess electricity to synthesize gas or produce heat [7]. These technologies can be applied to substitute fossil fuels in other energy sectors by using the excess electricity from curtailment. While this might not have been economically feasible thus far, the increasing number of hours during the year with curtailment events occurring potentially offer a much higher utilization of those assets than in the past. For example, a power-to-heat unit with 400 MW power input, could have used electricity from curtailment during 2.000 hours of the year 2015, given a location within the grid where it can help alleviate the majority of congestion events.

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[2] Data for Q3/Q4 2015 was extrapolated from Q1/Q2 2015.

[3] Due date at August 2015

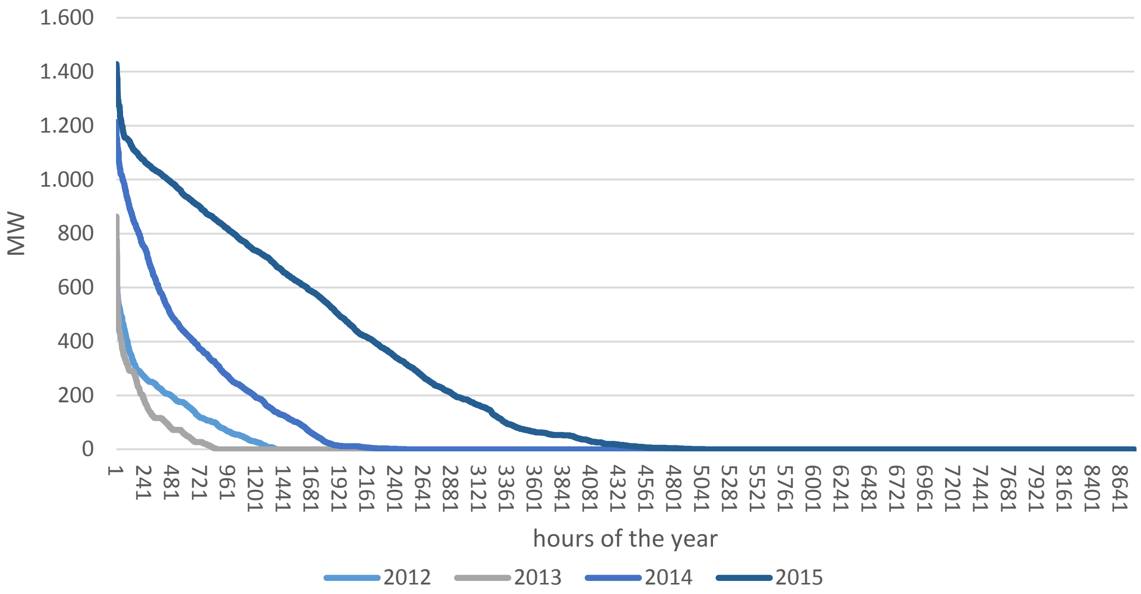

Fig. 6. Curtailment duration curve of wind power in Schleswig-Holstein (own calculation)

Fig. 7 shows the distribution of the simulated curtailment of renewable energy at the ten most affected grid nodes of the analyzed grid during winter 2015. These results help to identify those areas that are most affected by curtailment and to pinpoint locations where grid supporting infrastructure would add the most value (e.g. storage, power-to-heat, power-to-gas, etc.).

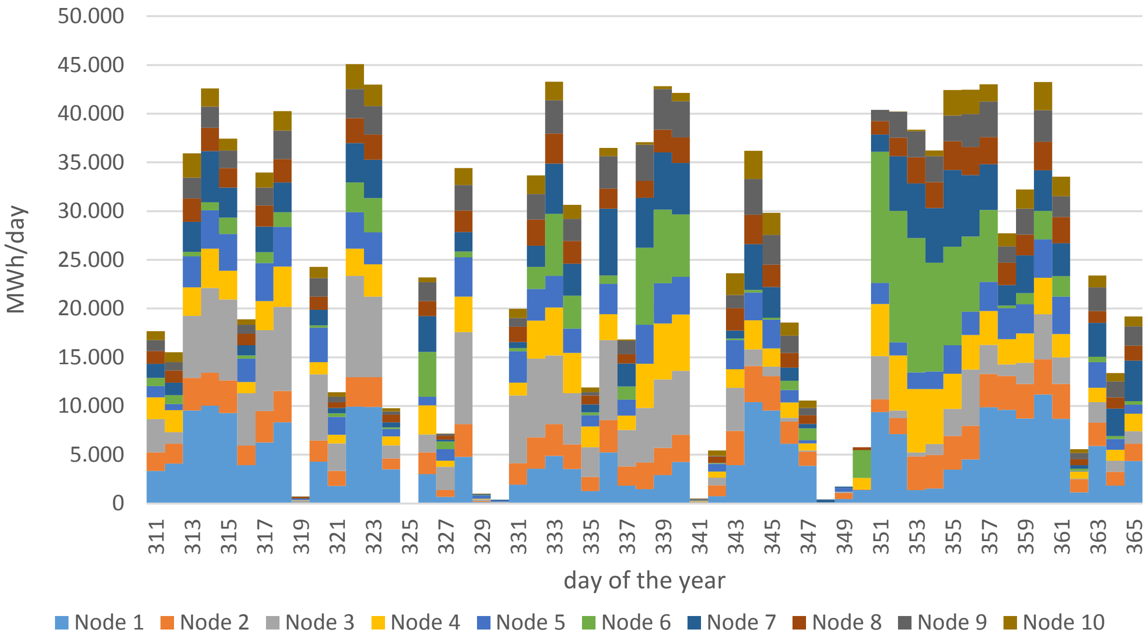

Fig. 7. Curtailed energy at the ten most affected nodes for a time period in winter 2015 (own calculation)

4 Critical discussion and Outlook

Over the last few years, we observed a steep increase in the curtailment of renewable energy in Germany. Almost half of the curtailment occurs within one distribution grid in Northern Germany, the grid that we are looking into in this work (SH Netz). Despite the rising problem of grid congestions and the resulting curtailments of renewable energy, foremost wind power plants, there have only been few analyses on the characteristics of these feed-in management activities.

This paper contributes to this discussion by conducting in-depth analyses of curtailment events within the distribution grid region of Schleswig Holstein, disaggregating the curtailment events on a high temporal and spatial dimension. This enables researchers working on the integration of renewables to get a better understanding of feed-in management activities and the resulting curtailment of renewables. While our results represent a step towards more transparency and data on curtailment of renewable energy, there is still much uncertainty present in our approach:

The public data available on the electricity grid infrastructure that we were looking at in this work is sparse and non-official. Our analysis and results of the years 2012-2013 rely heavily on the assumptions for capacity allocation. The spatial allocation of wind power plants to respective substations is purely done based on distances and ignores the fact that new substations, built only for the purpose of additional wind energy integration, will presumably have more capacity allocated to them. In addition, we focus in our presented approach on wind power curtailment, which represents roughly 90% of all curtailment, and neglect the remaining curtailment which adds additional uncertainty to our results. Furthermore, we used data from 50Hertz as a substitute, due to missing generation data of the Schleswig Holstein wind portfolio, to approximate the theoretical generation potential of wind power during curtailment events as the maximum amplitude of renewable supply.

Our results show that the increased amount of curtailed energy is caused by both an increase in the number of curtailment events as well as an increasing duration per event. From 2012 to 2015, the number of affected grid nodes facing curtailment within the distribution grid has risen from 12 to over 40 according to our analysis. The presented curtailment duration curves illustrate the growing potential for technologies that are able to utilize electricity that is subject to curtailment otherwise. Based in the right location, those technologies are gaining more and more hours of potential utilization.

We expect the increase in curtailment to continue over the course of the next years. Only when the extensive grid expansion projects currently under construction and in planning go online, we expect a reduction of curtailed electricity from renewable energy sources. However, the development over the past years shows that the grid expansion will likely not meet the pace of renewable expansion. Both congestion on the distribution and the transmission grid level have been increasing, leading to a growing amount of RES-E curtailment. Thus, alternative options to grid expansion, like storage, power-to-gas, power-to-heat and demand-side-management gain in importance and should be made applicable for grid congestion in distribution grids through regulation.

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