Locational (In)Efficiency of Renewable Energy Feed-in into the Electricity Grid: A Spatial Regression Analysis

IAEE Webinar

Tim Höfer and Reinhard Madlener

June 24, 2020
Background and motivation

Challenges

- Regional imbalance between electricity generation and consumption
- Variable electricity generation by renewables
- Electricity infeed into the distribution grid
- Reinforcement of the electricity grid is lagging behind

- Overstress of the electricity infrastructure
- Curtailment of power plants
- Compensation for the restrained electricity
- Passing on the costs to customers in the region concerned

Q1 Which drivers induce the occurrence of RES curtailment?

Q2 What are the regional curtailment costs of different renewables?
**Integration costs of renewables (Hirth et al., 2015)**

<table>
<thead>
<tr>
<th>Grid-related costs</th>
<th>Balancing costs</th>
<th>Profile costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opportunity costs of transporting electricity</td>
<td>Costs for forecasting errors of weather conditions</td>
<td>Costs for matching electricity supply and demand</td>
</tr>
</tbody>
</table>

**Related literature:**
- Quantifies the integration costs of renewables
- Qualitatively investigated the reasons for the occurrence of RES curtailment

**Merits of the paper:**
- Quantification of RES curtailment costs in a high spatial resolution
- Explanation of the correlation between renewables and RES curtailment
- Explanation of the impact of different renewables on RES curtailment costs

### Description of the study region

<table>
<thead>
<tr>
<th>Region</th>
<th>Wind energy capacity</th>
<th>PV system capacity</th>
<th>Electricity demand</th>
<th>RES curtailment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind dominated</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Low load</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>PV dominated</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

- **Wind dominated**: SHN
- **Low load**: Avacon, Edis
- **PV dominated**: Bayernwerk
Scope of the analysis

- 4 DSO regions
- 3 years (2015 – 2017)

- Voronoi tessellation
- High-to-medium voltage transformer stations

- 1,111 DSO subregions
- 3 years (2015 – 2017)
- 3,333 observations
Methodology

Two-step Heckit sample selection model

Step 1: Selection equation
- Probit model
- Corrects bias from non-randomly selected samples
- All subregion considered

\[ y_{1t}^* = \alpha_0 + \alpha_1 x_{1t} + \epsilon_1 \]
\[ y_{1t} = \begin{cases} 1, & y_{1t}^* > 0 \\ 0, & y_{1t}^* \leq 0 \end{cases} \]

Impact of renewables on the probability of occurrence of RES curtailment

Step 2: Output equation
- Spatial econometric model
- Captures cross-sectional dependence
- Only subregion with RES curtailment costs between 2015 – 2017

\[ y_{2it} = \beta_i + \beta x_{2it} + \theta \sum_{j=1}^{m} w_{ij} x_{2jt} + \epsilon_{it} \]
\[ e_{it} = \lambda_{i} f_{it} + \epsilon_{it} \]

Impact of renewables on RES curtailment costs

SLX = Spatial lag of X, CCE = Correlated common effects
Regression variables

Curtailment costs [€]

- Wind energy
- PV systems
- Bio energy
- Hydro energy
- Conventional power plants

Installed capacity [MW]

Generated electricity [GWh]

Distribution grid

- Load [GWh]
- Wind speed [m/s]
- DSO
- Year

DSO subregion

PV = Photovoltaic (including rooftop PV)
Calculating the dependent variable

1. Calculating the potential hourly electricity output of renewables during the curtailment measures
2. Computing the reduced power output of renewables stemming from curtailment measure
3. Determining the RES curtailment costs in the DSO subregion

RES = Renewable Energy Source, DSO = Distribution System Operator
Calculation of the load in the DSO subregions

Population of municipalities (LAU) → GVA per municipalities → Load factor (GVA per municipality / GVA Germany) → Electricity demand of municipalities → Electricity demand of DSO subregions

GVA of administrative district (NUTS 3) → Yearly electricity demand in Germany (NUTS 0) → Electricity demand of DSO subregions

GVA = Gross Value Added
## Regression results

<table>
<thead>
<tr>
<th></th>
<th>Installed capacity [MW]</th>
<th>Generated electricity [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Selection equation</td>
<td>Output equation</td>
</tr>
<tr>
<td>Wind</td>
<td>0.003*** (0.004)</td>
<td>0.007*** (0.002)</td>
</tr>
<tr>
<td>PV</td>
<td>0.003*** (0.002)</td>
<td>0.004 (0.005)</td>
</tr>
<tr>
<td>Bio</td>
<td>0.003** (0.005)</td>
<td>-0.003 (0.009)</td>
</tr>
<tr>
<td>Hydro</td>
<td>0.004 (0.032)</td>
<td>-0.035 (1.340)</td>
</tr>
<tr>
<td>Conventional</td>
<td>0.0001 (0.0003)</td>
<td>-0.001 (0.001)</td>
</tr>
<tr>
<td>Spatial Lag Wind</td>
<td>-0.0002 (0.002)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag PV</td>
<td>0.003 (0.008)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag Bio</td>
<td>0.007 (0.009)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag Hydro</td>
<td>-1.351 (2.007)</td>
<td>-0.386 (0.551)</td>
</tr>
<tr>
<td>Spatial Lag Conventional</td>
<td>-0.001 (0.002)</td>
<td>-0.001 (0.001)</td>
</tr>
<tr>
<td>Load [GWh]</td>
<td>-0.0004*** (0.0003)</td>
<td>-0.0004*** (0.0003)</td>
</tr>
<tr>
<td>(Adjusted) R²</td>
<td>0.309</td>
<td>0.469</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.897</td>
<td></td>
</tr>
<tr>
<td>Specificity</td>
<td>0.605</td>
<td></td>
</tr>
</tbody>
</table>

**Impact on likelihood of occurrence of RES curtailment per MW**

- Wind: + 0.3%
- PV: + 0.3%
- Bio: + 0.3%
- Load: - 0.04% [GWh]
## Regression results

<table>
<thead>
<tr>
<th></th>
<th>Installed capacity [MW]</th>
<th>Generated electricity [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Selection equation</td>
<td>Output equation</td>
</tr>
<tr>
<td>Wind</td>
<td>0.003*** (0.004)</td>
<td>0.007*** (0.002)</td>
</tr>
<tr>
<td>PV</td>
<td>0.003*** (0.002)</td>
<td>0.004 (0.005)</td>
</tr>
<tr>
<td>Bio</td>
<td>0.003** (0.005)</td>
<td>-0.003 (0.009)</td>
</tr>
<tr>
<td>Hydro</td>
<td>0.004 (0.032)</td>
<td>-0.035 (1.340)</td>
</tr>
<tr>
<td>Conventional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spatial Lag Wind</td>
<td>0.0001 (0.0003)</td>
<td>-0.001 (0.001)</td>
</tr>
<tr>
<td>Spatial Lag PV</td>
<td></td>
<td>-0.0002 (0.002)</td>
</tr>
<tr>
<td>Spatial Lag Bio</td>
<td></td>
<td>0.003 (0.008)</td>
</tr>
<tr>
<td>Spatial Lag Hydro</td>
<td>-1.351 (2.007)</td>
<td>-0.386 (0.551)</td>
</tr>
<tr>
<td>Spatial Lag Conventional</td>
<td>-0.001 (0.002)</td>
<td>-0.001 (0.001)</td>
</tr>
<tr>
<td>Load [GWh]</td>
<td>-0.0004*** (0.0003)</td>
<td>-0.0004*** (0.0003)</td>
</tr>
<tr>
<td>(Adjusted) R²</td>
<td>0.309</td>
<td>0.469</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.897</td>
<td>0.877</td>
</tr>
<tr>
<td>Specificity</td>
<td>0.605</td>
<td>0.596</td>
</tr>
</tbody>
</table>

**Impact on likelihood of occurrence of RES curtailment per GWh**

- Wind: + 0.07%
- PV: + 0.05%
- Bio: + 0.07%
- Load: - 0.04%
## Regression results

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>0.003*** (0.004)</td>
<td>0.007*** (0.002)</td>
<td>0.0007*** (0.0002)</td>
<td>0.002*** (0.001)</td>
</tr>
<tr>
<td>PV</td>
<td>0.003*** (0.002)</td>
<td>0.004 (0.005)</td>
<td>0.005*** (0.002)</td>
<td>0.002 (0.007)</td>
</tr>
<tr>
<td>Bio</td>
<td>0.003** (0.005)</td>
<td>-0.003 (0.009)</td>
<td>0.0007*** (0.0008)</td>
<td>-0.001 (0.002)</td>
</tr>
<tr>
<td>Hydro</td>
<td>0.004 (0.032)</td>
<td>-0.035 (1.340)</td>
<td>0.002 (0.008)</td>
<td>-0.229 (0.367)</td>
</tr>
<tr>
<td>Conventional</td>
<td>0.0001 (0.0003)</td>
<td>-0.001 (0.001)</td>
<td>0.00 (0.0002)</td>
<td>-0.001 (0.001)</td>
</tr>
<tr>
<td>Spatial Lag Wind</td>
<td>-0.0002 (0.002)</td>
<td></td>
<td>0.001 (0.001)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag PV</td>
<td>0.003 (0.008)</td>
<td></td>
<td>0.010 (0.010)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag Bio</td>
<td>0.007 (0.009)</td>
<td></td>
<td>0.002 (0.002)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag Hydro</td>
<td>-1.351 (2.007)</td>
<td></td>
<td>-0.386 (0.551)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag Conventional</td>
<td>-0.001 (0.002)</td>
<td></td>
<td>-0.001 (0.001)</td>
<td></td>
</tr>
<tr>
<td>Load [GWh]</td>
<td>-0.0004*** (0.0003)</td>
<td></td>
<td>-0.0004*** (0.0003)</td>
<td></td>
</tr>
<tr>
<td>(Adjusted) R²</td>
<td>0.309</td>
<td>0.469</td>
<td>0.273</td>
<td>0.476</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.897</td>
<td></td>
<td>0.877</td>
<td></td>
</tr>
<tr>
<td>Specificity</td>
<td>0.605</td>
<td></td>
<td>0.596</td>
<td></td>
</tr>
</tbody>
</table>

**Impact on RES curtailment costs per MW**

- **Wind**: + 0.7%
### Regression results

<table>
<thead>
<tr>
<th></th>
<th>Installed capacity [MW]</th>
<th>Generated electricity [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Selection equation</td>
<td>Output equation</td>
</tr>
<tr>
<td>Wind</td>
<td>0.003*** (0.004)</td>
<td>0.007*** (0.002)</td>
</tr>
<tr>
<td>PV</td>
<td>0.003*** (0.002)</td>
<td>0.004 (0.005)</td>
</tr>
<tr>
<td>Bio</td>
<td>0.003** (0.005)</td>
<td>-0.003 (0.009)</td>
</tr>
<tr>
<td>Hydro</td>
<td>0.004 (0.032)</td>
<td>-0.035 (1.340)</td>
</tr>
<tr>
<td>Conventional</td>
<td>-0.001 (0.003)</td>
<td>-0.001 (0.001)</td>
</tr>
<tr>
<td>Spatial Lag Wind</td>
<td>-0.0002 (0.002)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag PV</td>
<td>0.003 (0.008)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag Bio</td>
<td>0.007 (0.009)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag Hydro</td>
<td>-1.351 (2.007)</td>
<td>-0.386 (0.551)</td>
</tr>
<tr>
<td>Spatial Lag Conventional</td>
<td>-0.001 (0.002)</td>
<td>-0.001 (0.001)</td>
</tr>
<tr>
<td>Load [GWh]</td>
<td>-0.0004*** (0.0003)</td>
<td>-0.0004*** (0.0003)</td>
</tr>
<tr>
<td>(Adjusted) R²</td>
<td>0.309</td>
<td>0.469</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.897</td>
<td></td>
</tr>
<tr>
<td>Specificity</td>
<td>0.605</td>
<td></td>
</tr>
</tbody>
</table>

**Impact on RES curtailment costs per GWh**

- Wind: + 0.02%
### Regression results

<table>
<thead>
<tr>
<th></th>
<th>Installed capacity [MW]</th>
<th>Generated electricity [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Selection equation</td>
<td>Output equation</td>
</tr>
<tr>
<td>Wind</td>
<td>0.003*** (0.004)</td>
<td>0.007*** (0.002)</td>
</tr>
<tr>
<td>PV</td>
<td>0.003*** (0.002)</td>
<td>0.004 (0.005)</td>
</tr>
<tr>
<td>Bio</td>
<td>0.003** (0.005)</td>
<td>-0.003 (0.009)</td>
</tr>
<tr>
<td>Hydro</td>
<td>0.004 (0.032)</td>
<td>-0.035 (1.340)</td>
</tr>
<tr>
<td>Conventional</td>
<td>0.0001 (0.0003)</td>
<td>-0.001 (0.001)</td>
</tr>
<tr>
<td>Spatial Lag Wind</td>
<td>-0.0002 (0.002)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag PV</td>
<td>0.003 (0.008)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag Bio</td>
<td>0.007 (0.009)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag Hydro</td>
<td>-1.351 (2.007)</td>
<td></td>
</tr>
<tr>
<td>Spatial Lag Conventional</td>
<td>-0.001 (0.002)</td>
<td></td>
</tr>
<tr>
<td>Load [GWh]</td>
<td>-0.0004*** (0.0003)</td>
<td>-0.0004*** (0.0003)</td>
</tr>
<tr>
<td>(Adjusted) R²</td>
<td>0.309</td>
<td>0.469</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.897</td>
<td>0.877</td>
</tr>
<tr>
<td>Specificity</td>
<td>0.605</td>
<td>0.596</td>
</tr>
</tbody>
</table>

* Most affected subregions (4th quartile)

- Wind: 28,300 €/MW/a*
- Wind: 8.1 €/MWh*
Conclusions and political implications

**Procedure**

- Investigating the impacts of implementing renewables into an inflexible energy system
- Analyzing the regionally varying costs of curtailing renewables to stabilize the electricity infrastructure

**Results**

- Most DSO subregions do not experience RES curtailment to a large extent
- Especially wind energy induces high RES curtailment costs in northern and eastern Germany

**Recommendations**

- Setting regionally varying price signals for renewables
- Setting incentives for flexibility options

RES = Renewable Energy Source, DSO = Distribution System Operator
Thank you for your attention

Contact details:
Institute for Future Energy Consumer Needs and Behavior (FCN)
E.ON Energy Research Center
Mathieustraße 10
52074 Aachen
Germany

Tim Höfer
THoefer@eonerc.rwth-aachen.de
T +49 241 80 49837, 49820
http://www.eonerc.rwth-aachen.de/FCN

Prof. Dr. Reinhard Madlener
RMadlener@eonerc.rwth-aachen.de
T +49 241 80 49820
## Aims and merits

Quantifying the effect of different renewable energy technologies on regional RES curtailment

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Elucidate why RES curtailment occurs only in some regions of Germany and not in others</td>
</tr>
<tr>
<td>2</td>
<td>Analyze the correlation of installed capacity and generated electricity of renewables and RES curtailment costs.</td>
</tr>
<tr>
<td>3</td>
<td>Calculate the regionally disaggregated amount and costs of RES curtailment in a higher spatial resolution than available in official publications.</td>
</tr>
<tr>
<td>4</td>
<td>Give policy recommendations based on the results</td>
</tr>
</tbody>
</table>

RES = Renewable Energy Source
Explanatory variables

Wind energy capacity

PV system capacity

Biomass capacity
Explanatory variables

Hydroelectric capacity

Load

Mean wind speed
Descriptive statistics for the dependent variable and the explanatory variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Year</th>
<th>Mean</th>
<th>Std.dev.</th>
<th>Min</th>
<th>Max</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>RES curtailment cost</td>
<td>[€]</td>
<td>2015–2017</td>
<td>286,737</td>
<td>1,385,723</td>
<td>0</td>
<td>23,722,656</td>
<td>763,868,462</td>
</tr>
<tr>
<td>Wind energy</td>
<td>[MW]</td>
<td>2017</td>
<td>63.4</td>
<td>52.0</td>
<td>0</td>
<td>625</td>
<td>27,887</td>
</tr>
<tr>
<td>PV systems</td>
<td>[MW]</td>
<td>2017</td>
<td>17.0</td>
<td>20.4</td>
<td>0</td>
<td>216</td>
<td>15,105</td>
</tr>
<tr>
<td>Bio energy</td>
<td>[MW]</td>
<td>2017</td>
<td>3.5</td>
<td>6.4</td>
<td>0</td>
<td>140</td>
<td>3,118</td>
</tr>
<tr>
<td>Hydro energy</td>
<td>[MW]</td>
<td>2017</td>
<td>0.4</td>
<td>1.4</td>
<td>0</td>
<td>16</td>
<td>389</td>
</tr>
<tr>
<td>Conv. peak-load</td>
<td>[MW]</td>
<td>2017</td>
<td>17.0</td>
<td>99.5</td>
<td>0</td>
<td>1,770</td>
<td>15,101</td>
</tr>
<tr>
<td>Load</td>
<td>[GWh]</td>
<td>2017</td>
<td>146.9</td>
<td>327.3</td>
<td>5.8</td>
<td>7,441</td>
<td>130,480</td>
</tr>
<tr>
<td>Wind speed</td>
<td>[W/m²]</td>
<td>2015–2017</td>
<td>7.7</td>
<td>0.9</td>
<td>3.4</td>
<td>9.6</td>
<td></td>
</tr>
<tr>
<td>Wind energy</td>
<td>[GWh]</td>
<td>2017</td>
<td>67.2</td>
<td>159.8</td>
<td>0</td>
<td>1,619</td>
<td>59,715</td>
</tr>
<tr>
<td>PV systems</td>
<td>[GWh]</td>
<td>2017</td>
<td>14.0</td>
<td>17.0</td>
<td>0</td>
<td>191</td>
<td>12,379</td>
</tr>
<tr>
<td>Bio energy</td>
<td>[GWh]</td>
<td>2017</td>
<td>18.6</td>
<td>34.8</td>
<td>0</td>
<td>758</td>
<td>16,747</td>
</tr>
<tr>
<td>Hydro energy</td>
<td>[GWh]</td>
<td>2017</td>
<td>1.6</td>
<td>5.1</td>
<td>0</td>
<td>57</td>
<td>1,419</td>
</tr>
<tr>
<td>Conv. peak-load</td>
<td>[GWh]</td>
<td>2017</td>
<td>32.7</td>
<td>195.9</td>
<td>0</td>
<td>3,670</td>
<td>29,067</td>
</tr>
</tbody>
</table>
Comparison of ENTSO-E data and model outcome

Hourly wind electricity generation in Germany in 2015

Electricity generation [MWh]

Model
ENTSO–E
Corr = 0.95

Hours
Comparison of ENTSO-E data and model outcome

Hourly wind electricity generation in Germany in 2016

- Model
- ENTSO–E

\[ \text{Corr} = 0.94 \]
Comparison of ENTSO-E data and model outcome

Hourly wind electricity generation in Germany in 2017

Model
ENTS0E
Corr = 0.93
Comparison of ENTSO-E data and model outcome

Hourly PV electricity generation in Germany in 2015

Model
ENTSO-E

Corr = 0.93
Comparison of ENTSO-E data and model outcome

Hourly PV electricity generation in Germany in 2016

Model
ENTS0-E

Corr = 0.93
Comparison of ENTSO-E data and model outcome

Hourly PV electricity generation in Germany in 2017

Model

ENTSOno–E

Corr = 0.94
Comparison of calculated and published RES curtailment costs

<table>
<thead>
<tr>
<th>DSO¹</th>
<th>Federal States (FS)²</th>
<th>Area covered [%] ³</th>
<th>Year</th>
<th>DSO costs [€]⁴</th>
<th>FS costs [€]⁵</th>
<th>Share [%]⁶</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avacon</td>
<td>Lower Saxony, Saxony-Anhalt, Hesse</td>
<td>59.7⁴</td>
<td>2015</td>
<td>6,514,760</td>
<td>57,908,856</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2016</td>
<td>5,718,869</td>
<td>31,223,962</td>
<td>18.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2017</td>
<td>37,465,927</td>
<td>180,712,239</td>
<td>20.7</td>
</tr>
<tr>
<td>BW</td>
<td>Bavaria</td>
<td>57.8</td>
<td>2015</td>
<td>41,105</td>
<td>333,345</td>
<td>12.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2016</td>
<td>58,891</td>
<td>292,782</td>
<td>20.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2017</td>
<td>332,192</td>
<td>585,290</td>
<td>39.7</td>
</tr>
<tr>
<td>Edis</td>
<td>Brandenburg, Mecklenburg-Western Pomerania</td>
<td>71.7</td>
<td>2015</td>
<td>45,574,389</td>
<td>96,229,679</td>
<td>47.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2016</td>
<td>26,910,325</td>
<td>63,301,645</td>
<td>42.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2017</td>
<td>26,910,325</td>
<td>62,246,651</td>
<td>43.2</td>
</tr>
<tr>
<td>SHN</td>
<td>Schleswig-Holstein</td>
<td>99.4⁶</td>
<td>2015</td>
<td>265,360,723</td>
<td>312,942,279</td>
<td>84.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2016</td>
<td>126,665,577</td>
<td>273,012,271</td>
<td>48.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2017</td>
<td>200,474,705</td>
<td>351,246,341</td>
<td>57.1</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td></td>
<td>2015</td>
<td>317,517,978</td>
<td>467,414,159</td>
<td>68.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2016</td>
<td>181,267,336</td>
<td>368,430,660</td>
<td>43.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2017</td>
<td>265,083,149</td>
<td>594,818,522</td>
<td>44.6</td>
</tr>
</tbody>
</table>

¹ Avacon = Avacon Netz AG, BW = Bayernwerk Netz GmbH, Edis = E.DIS Netz AG, SHN = Schleswig-Holstein Netz AG.
² Federal states in which the respective DSO operates.
³ Share of federal state area covered by respective DSO.
⁴ RES curtailment costs in the respective DSO region as calculated in this study.
⁵ RES curtailment costs in the respective German federal states as published by the German Federal Network Agency (BNetzA, 2017d, 2018b).
⁶ Share of calculated to published RES curtailment costs.
Marginal costs of renewables per quartile

<table>
<thead>
<tr>
<th>Variables</th>
<th>Unit</th>
<th>1st Q.</th>
<th>2nd Q.</th>
<th>3rd Q.</th>
<th>4th Q.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind energy</td>
<td>€/MW</td>
<td>18</td>
<td>302</td>
<td>2,939</td>
<td>28,277</td>
</tr>
<tr>
<td>Wind energy</td>
<td>€/MWh</td>
<td>0.005</td>
<td>0.10</td>
<td>0.80</td>
<td>8.10</td>
</tr>
</tbody>
</table>

The costs only apply for regions that experienced RES curtailment in the three consecutive years from 2015—2017.