Climatological Analysis of the Solar and Wind Energy Potential in Germany

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Motivation of this study

• Increased share of solar and wind energy in European energy production
• Solar radiation and wind depending on weather and are highly variable
• Analysis of the variability of produced energy by calculating capacity factors for Germany

$$\text{CF} = \frac{\text{produced energy}}{\text{installed capacity}}$$

- Particularly the very low energy production events, so-called shortfall events are problematic
  - how often?
- Occurrence at which Großwetterlage (GWL)?
- Balancing effects in Europe?
Data
Solar Capacity Factor

Data
- based on CM SAF SARAH-2 data record
  - global / direct radiation

Resolution
- Temporal: 30 minutes
- Spatial: 5 km x 5 km

Coverage
- Germany, 1995 - 2015

Auxillary Data
- 2m-temperature (COSMO-REA6)
- Assumption tilt angle: angle distribution*
  - centered: 20° inclination angle,
    southward azimuth angle
Solar Capacity Factor - Methods

Calculating radiation on tilted surface
R-package “solaR” (Lamiguerio, 2016)

Modelled PV-modules
Standard Test Conditions
(Huld und Gracia Amillo, 2015)

Sensitivity Studies
Optimum Inclination and Azimuth Angle

Assumption tilt angle
Frequency distribution
(Saint-Drenan et al. 2018)
Wind Capacity Factor

**Data**

Based on regional reanalysis COSMO REA6

- 100m-wind speed

**Resolution**

Temporal: hourly

Spatial: 5 km x 5 km

**Coverage**

Germany, 1995 - 2015

**Assumption**

Power Curve* of a modern wind turbine (116m height);
Implementation in R package “bReeze”

Open Power System Data

web platform with energy data
https://open-power-system-data-data.org/

Data
Collection of publicly available data
➤ Quality-checked, processed and documented

Content
➤ Time series data of installed capacity
➤ Actual power generation
➤ Individual power plants

EMHIRES Data Set

web platform with European CF
https://setis.ec.europa.eu/EMHIRES-datasets

Data
- Collection of publicly available data
- Solar CF based on CM SAF SARAH
- Wind CF based on MERRA

Content
- Time series data of 28 European countries from 1986 - 2015
- Actual power generation
Methods
Data Processing – Time Series

Example SOLAR

Solar Capacity Factor in Germany
02.05.2015 09:00 UTC

Electrical Capacity of Solar Plants per Gridcell in Germany, 2015

Consider locations and installed capacity from 2015

Spatial Sum for Germany

Weighted Fieldsum, Diurnal Cycle
02 May 2015, Germany, 30min Data

÷ mean installed capacity 2015
Calibration of the simulated Capacity Factor

- Measurement data based on Open Power System Data (OPSD)
  - Temporal resolution: hourly
- Simulated CF are calibrated with linear fit (normalised at 2015)
- High correlation between simulated solar and wind CF and the CF from measurement data
Simulated Generated Power

Conversion of CF in produced energy

- Mean installed Capacity 2015:
  - 38 GW Solar
  - 40 GW Wind

- Produced Energy 2015:
  - 35 TWh Solar
  - 75 TWh Wind
  \[\text{\textbf{110 TWh Sum}}\]
Results
Annual Sum / Mean Monthly Sum 1995 - 2015

- ~ 102 TWh mean yearly production due to solar and wind energy*
- Wind energy dominates in fall / winter
- Solar and wind energy have an equal share in summer

*Assumption: installed capacity normalised to 2015 for all years
**Mean Annual Cycle 1995 - 2015**

- More energy production due to wind energy in principle, but therefore higher variability than solar energy
Mean Annual Cycle 1995 - 2015

- Relatively constant energy production throughout the year
- All low energy production events occur in fall / winter
Impact of „Grosswetterlagen“ (GWL)

- Using GWL classification of James, P.M., 2007
- Clear dependency of wind / solar CF on weather regimes

James, P.M., 2007, An objective classification method of Hess and Brezowsky Grosswetterlagen over Europe, Theoretical and applied Climatology, 88, 17-42
Shortfall Events

**Def.: Shortfall Events**
- Specific period of time, where low energy production occur due to sun and wind

**Occurence of Shortfall Events**
- Considering 20 lowest energy production events
- All shortfall events occur in fall / winter independent on event length
Shortfall Events

**Length of shortfall events for further analysis**

- 120h; taking the 20 lowest events
- GWL „9“ (High over Central Europe) is the most frequent GWL at shortfall events
### Shortfall Events (120h) 1995 - 2015

<table>
<thead>
<tr>
<th>Event Start</th>
<th>Event End</th>
<th>GWL</th>
<th>Solar+Wind</th>
<th>Solar</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>05.01.1997 08:00</td>
<td>10.01.1997 07:00</td>
<td>HB (16) HNA (14)</td>
<td>295 (59)</td>
<td>69 (14)</td>
<td>226 (45)</td>
</tr>
<tr>
<td>22.12.2006 14:00</td>
<td>27.12.2006 13:00</td>
<td>HM (9)</td>
<td>300 (60)</td>
<td>135 (27)</td>
<td>165 (33)</td>
</tr>
<tr>
<td>1995 - 2015</td>
<td></td>
<td></td>
<td>1415 (283)</td>
<td>455 (91)</td>
<td>965 (193)</td>
</tr>
</tbody>
</table>

- During the shortfall event (120h) only 10% of the daily mean is produced.
Analysis of Shortfall Event 22. - 27.12.2006 (GWL 9)

- Negative wind speed anomaly in Germany leads to low wind energy production at this event (17 % of daily mean)
- Negative cloud fraction anomaly over Germany during GWL 9 in winter; individual events related to fog / low clouds possible
Analysis of Shortfall Event 22. - 27.12.2006 (GWL 9)

High wind CF in Scandinavia (29 %), Croatia (31 %) and Slovenia (28 %) allow the balancing of the low wind CF (9 %) in Germany at this event.
Mean Wind CF / Mean Solar CF in Winter at GWL 9*

European wind CF / solar CF distribution at the low production event is similar to the general wind CF / solar CF distribution at GWL 9

*All GWL 9 events from 1995 to 2015 (Winter) included
Summary

• Successfully **simulate Capacity Factors (CF)** based on satellite data (solar) and reanalysis data (wind)

• Validation and conversion of CF in **produced energy** (GWh) with Open Power System Data

• Clear **dependency** of wind / solar power generation on **weather regimes** (GWL)

• Identifying low energy production events (**shortfall events**) with event length of 120h from 1995 to 2015

• **Balancing effects** for Germany with Scandinavia, Croatia or Slovenia possible