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On the inter-annual variability of wind energy generation – A case study from Germany

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HIGHLIGHTS

- Methodology to quantify inter-annual variability of national wind energy generation.
- High-spatial resolution (200 m × 200 m) annual 3D wind field reconstruction.
- Estimation of (non)-exceedance probability of annual wind energy generation.
- Variation of annual wind energy generation between 67 and 112 TWh/yr.
- Variation of annual greenhouse gas mitigation between 45.6 and 76.3 Mio. tCO_2-equiv.

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ABSTRACT

The intermittent and stochastic nature of the wind resource complicates constant electricity supply in countries with high wind energy share in the electricity mix. Therefore, the goal of this study was to quantify the inter-annual variability of wind energy generation on the national scale by estimating upper and lower limits of annual wind energy generation (*WEG*). A novel methodology was developed and is presented for Germany, where onshore wind energy already accounts for more than 15% of net electricity consumption. First, a comprehensive wind turbine data set was produced including all onshore wind turbines operating in 2017. Next, the wind speed-wind shear model (WSWS) was used to reconstruct the high spatial resolution (200 m × 200 m) annual wind speed distributions in the wind turbine hub height range 30–179 m above ground level in the period 1979–2017. By using wind turbine-specific power curves, the annual wind energy yield was calculated for each wind turbine. It was summed up for the entire country, yielding *WEG*. Then, 16 theoretical distributions were fitted to *WEG*. From the fitted distributions, long-term return values of *WEG* were calculated. In a 100-year period (probability 98%), *WEG* lies between 67 and 112 TWh/yr and the annual greenhouse gas mitigation potential varies between 45.6 and 76.3 Mio. tCO_2-equiv. under current climate. The great *WEG*-range emphasizes the importance of considering upper and lower *WEG*-limits for ensuring constant electricity supply at the national scale.

1. Introduction

Mitigation of climate change requires increasing energy supply by renewable energies. One renewable energy, which has the potential to cover large amounts of the electricity demand, is wind energy [1,2]. At the end of 2017, the global cumulative installed wind capacity was 539,581 MW [3]. The largest wind capacity is installed in China (188,232 MW), the USA (89,077 MW), and Germany (56,132 MW). More than 5,000 MW new capacity were installed in 2017 in China (19,500 MW), the USA (7,017 MW), and Germany (6,581 MW). In addition, in many other countries such as the United Kingdom, India, Brazil, and France there is great interest to further increase the share of wind energy in the future electricity mix.

In many studies, the mean annual wind energy yield ($\overline{AEY}$) of a wind turbine is taken as reference unit to quantify the wind resource. Serri et al. [4] estimated the repowering potential of wind turbines in Italy using $\overline{AEY}$. In another study [5], a novel boundary layer scaling technique for estimating $\overline{AEY}$ was applied in Great Britain. By using orographic and land use characteristics, $\overline{AEY}$ for a 2.5-MW wind turbine was modeled in Southwest Germany with a least-squares boosting algorithm [6]. These studies are beneficial to improve wind turbine siting, which leads to a higher share of wind energy in the electricity

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Nomenclature

Acronyms

agl	above ground level
cdf	cumulative distribution function
ecdf	empirical cumulative distribution function
LMOM	L-moment method
LSE	least squares estimation method
MLE	maximum likelihood estimation method
MOM	moment method
pdf	probability density function
PEM	parameter estimation method
WSWS	wind speed-wind shear model

Symbols

$\bar{h}$	mean height (m agl)
$\overline{AEY}$	mean annual wind energy yield (GWh/yr)
$\hat{F}\ ()$	estimated cumulative distribution function
$\bar{P}$	mean power (MW)
$P_W(U_{hub})$	wind turbine power curve (MW)
$\bar{U}$	mean wind speed (m/s)
$\overline{WEG}$	mean annual wind energy generation at the national scale (TWh/yr)
$\hat{\rho}$	copula parameter
AEY	annual wind energy yield (GWh/yr)
APE	absolute percentage error (%)
cf	capacity factor
E	wind shear exponent
EP	exceedance probability (%)
F()	cumulative distribution function
f()	probability density function
h	height (m agl)
i	index for wind turbine
IAV	inter-annual variability
k	first shape parameter
KS	Kolmogorov-Smirnov statistic
n	number of hours in a year
N	total number of onshore wind turbines operating in 2017
NEP	non-exceedance probability (%)
NP	number of parameters
p-value	probability-value
RL	return level (yr)
S	standard deviation of *AEY* (GWh/yr)
U	wind speed (m/s)
WEG	annual wind energy generation at the national scale (TWh/yr)
WFE	wind farm efficiency
WTA	wind turbine availability
y	counter
α	first scale parameter
γ	second scale parameter
$\Gamma()$	Gamma function
μ	location parameter
δ	second shape parameter

Subscripts

1000 m	1000 m above ground level
140 m	140 m above ground level
act	actual
AEY	annual wind energy yield
cf	capacity factor
hub	wind turbine hub height
r	rated

mix.

Summing up $\overline{AEY}$ for all wind turbines in a country yields the mean annual wind energy generation ($\overline{WEG}$). For example, in Germany, the geographically and technically feasible $\overline{WEG}$ was estimated at 860 TWh/yr [7]. Based on $\overline{AEY}$, Lu et al. [8] estimated that a worldwide network of land-based 2.5-MW wind turbines could generate 690 PWh/yr of wind energy.

However, in contrast to many conventional energies, the intermittent and stochastic nature of the wind resource complicates constant electricity supply [9–11]. The high variability of wind energy generation is initially caused by spatiotemporal changes of the wind vector. The absolute value and direction of the wind vector varies in three dimensions from sub-hourly [12], hourly [13,14], daily [15], monthly/seasonal [16–20], annual [21–24] to multi-decadal [25,26] scales, depending on atmospheric conditions.

Considering that wind speed (*U*) is characterized by a high spatiotemporal variability, it is clear that both annual wind energy yield (*AEY*) and annual wind energy generation (*WEG*) also greatly vary. Since mosaic-like land cover pattern and orography highly influence *AEY*-calculations, it is important to reconstruct *U* on the highest possible spatial scale [23]. Moreover, the variation of hub height among the installed wind turbines requires a representation of the wind speed field not only in both horizontal directions, but also in vertical direction [27].

In many countries the variability of recent *WEG*-values is superimposed by a strong increase of wind capacity. Therefore, the exceedance (*EP*) and non-exceedance (*NEP*) probability of *WEG*-values cannot easily be estimated. In addition, short operating periods of most wind turbines prevent a detailed assessment of long-term variations of wind energy production. Furthermore, historical energy outputs from wind turbines operating in recent years are available only to a limited extent.

Switching towards renewable energies, the variability of *WEG* must be known and taken adequately into account. Moreover, if *WEG*-values are clearly below $\overline{WEG}$, then the inter-annual variability will pose a great risk to a steady and reliable electricity supply. If *WEG* is low, other energy sources must be available to close the supply gap. To this end, the capacities of these other energy sources must be maintained and available. The quantification of the lower supply limit provides important information regarding the minimum capacity of constantly available energy sources. On the other hand, the quantification of upper *WEG*-limits provides important information regarding possible energy storage potentials. Thus, the goals of this study are to (1) reconstruct the annual wind speed distributions in the hub height range on a high-spatial resolution grid (200 m × 200 m), (2) estimate *WEG* in the climatologically representative period 1979–2017, and (3) assess *EP* and *NEP* of *WEG* for long-term return levels (*RL*) to provide upper and lower *WEG*-limits.

2. Material and methods

The study area is the mainland of Germany. The assessment of the inter-annual variability of onshore *WEG* includes the following steps (Fig. 1): (1) compilation of wind turbine data of Germany's onshore wind turbines operating in 2017 which correspond to 89.7% of Germany's total installed capacity, (2) reconstruction of the annual wind speed distributions in hub height range in the period 1979–2017 on a high-spatial resolution grid (200 m × 200 m), (3) estimation of *AEY* for all wind turbines for every year in 1979–2017, (4) estimation of *WEG* in 1979–2017 based on *AEY*, (5) applying trend tests to *WEG*-time series