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Achieving Germany's wind energy expansion target with an improved wind turbine siting approach

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ABSTRACT

The goals of this study were to develop and to evaluate wind turbine siting scenarios for achieving a share of about 40% (250 TWh/yr) wind energy in Germany's gross electricity consumption. The scenarios were developed to quantify the influence of (1) available technology and repowering, (2) resource distribution, and (3) siting strategy on five siting suitability measures: (1) number of wind turbines, (2) cumulative installed capacity, (3) capacity factor, (4) main investment costs, and (5) distribution of wind turbines. The wind field in the analyzed hub height range was modeled by the wind speed-wind shear model on a 200 m × 200 m grid. Geographically restricted areas were considered as not suitable under all scenarios. For a better comparison of the scenarios, a novel wind turbine siting index was introduced by normalizing the suitability measures. It was found that an installed capacity of less than 100 GW and about 36,000 wind turbines are sufficient to generate 250 TWh/yr wind energy. If the current rate of wind energy expansion in Germany is maintained, this value can be achieved in the early 2030s. The results also demonstrate that inefficient wind turbine siting considerably extends the period and increases the number of required wind turbines. Against this background, the results of this study can be applied for a better coordination of wind turbine siting in Germany at different administrative levels. The methodology is portable to other countries and can be used to develop national siting strategies to achieve projected wind energy shares in the electricity mix.

1. Introduction

Wind energy will play an important role in mitigating climate change since it has the potential to cover a large amount of the global electricity demand [1]. The global cumulative installed wind capacity already reached 539,581 MW in 2017 [2] and there is great interest to further increase the share of wind energy in the electricity mix in many countries.

A common way to describe the suitability of an area for utilizing wind as an energy source is the wind energy potential [3]. The wind energy potential can hierarchically be split up into the meteorological potential, the geographical potential, the technological potential, the economic potential, and the implementation potential.

The meteorological potential is determined by the available wind resource [3]. It can be defined by wind speed (U), which is characterized by a high spatiotemporal variability. Therefore, theoretical wind speed distributions are often used to describe its statistical behavior [4]. In previous studies, the parameters of wind speed distributions were mapped on high-spatial resolution grids covering different study areas. For instance, the parameters of the Weibull distribution were mapped in the United Kingdom based on surface properties and meteorological data (1 km × 1 km resolution) in 10 m above ground level (agl) [5]. Using a LS-Boost approach, the parameters of the Wakeby distribution were estimated for Southwest Germany in 100 m agl on a 50 m × 50 m resolution grid [6]. However, due to the vertical wind shear, the wind speed distribution from one wind turbine hub height (h_{hub}) cannot simply be transferred to other hub heights [7]. To address this problem, the wind speed-wind shear model (WSWS) was developed [8]. It can be used to estimate statistical wind speed distributions in heights from 10 to 200 m agl. In a previous study, its parameters were mapped in Germany based on surface features and ERA-Interim reanalysis wind speed data [9].

The geographical potential excludes restricted areas from the meteorological potential [3]. On a global scale, ice-cover, permafrost, lakes, urban areas, wetlands, evergreen forests, sloped areas, and conservation areas are not included in the geographical potential [1]. On a regional scale, further land use constraints such as railways, airports, or culture and recreation areas have to be taken into account [10]. In a previous study, the geographical potential was estimated on a 50 m × 50 m resolution grid for the German federal state Baden-

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Nomenclature

Abbreviation and acronyms

agl	above ground level
BA	Bavaria
BE	Berlin
BR	Bremen
BB	Brandenburg
BW	Baden-Württemberg
CL	closed wind turbines
CU	current wind turbines
EGG	electricity generation goal (in this study: 250 TWh/yr)
HA	Hamburg
HE	Hesse
LS	Lower Saxony
MV	Mecklenburg-Vorpommern
NEW	newly installed wind turbines
NRW	North-Rhine-Westphalia
pdf	probability density function
RE	repowered wind turbines
RP	Rhineland-Palatinate
SA	Saxony
SAA	Saxony-Anhalt
SL	Saarland
SC	wind turbine siting scenario
SH	Schleswig-Holstein
TH	Thuringia
WSWS	wind speed-wind shear model
WTT	wind turbine type

Symbols

$\overline{AEY}$	mean annual average energy yield over all wind turbines (GWh/yr)
$\overline{LCOE}$	mean levelized costs of electricity (€/kWh)
$\overline{U}$	mean wind speed (m/s)
$\overline{cf}$	mean capacity factor over all wind turbines
$\hat{\rho}$	copula parameter
A	total annual costs (€)
AEY	annual average energy yield (GWh/yr)
cc	cumulative capacity (MW)
cf	capacity factor
D	total number of districts
Dur	duration (yr)
E	wind shear exponent
$f()$	probability density function
h	height (m agl)
i	counter for SSM
I	main investment costs (€)
II	incidental investment costs (€)
ir	real interest rate
$LCOE$	levelized costs of electricity (€/kWh)
max	maximum
min	minimum
N	wind turbine lifetime (20 yr)
n	number of hours in a year (8760 h)
P	power (kW)
$P_w(h_{hub})$	wind turbine power curve (kW)
s	standard deviation of wind turbines per district
SSI	siting suitability index
SSM	siting suitability measure
U	wind speed (m/s)
WFE	wind farm efficiency
WTA	wind turbine availability
WTN	number of wind turbines

Subscripts

$1000\,m$	1000 m agl
$140\,m$	140 m agl
CL	closed wind turbines
CU	current wind turbines
d	counter for district
hub	wind turbine hub height
i	counter for SSM
max	maximum
min	minimum
NEW	newly installed wind turbines
r	rated
RE	repowered wind turbines
t	year
WTT	wind turbine type

Wuerttemberg as a function of h_{hub} [11].

The technical potential is defined as the total extractable wind energy by applying the current wind turbine technology [3]. Estimates of the global technical wind energy potential greatly vary between investigations and are often based on fairly coarsely resolved reanalysis wind speed data. Lu et al. [12] reported that 2.5 MW onshore wind turbines can extract 1100 PWh/yr wind energy from the atmosphere, whereas Miller et al. [13] came to the conclusion that the technical wind energy potential varies in the range 158–596 PWh/yr. On the national scale, the technical wind energy potential is often evaluated on a higher spatial resolution to account for the small-scale variability of the meteorological and geographical potential. McKenna et al. [14] estimated the technical potential in Germany at around 860 TWh/yr by using 1 km × 1 km wind speed data.

The economic potential is defined as the technical potential which can be realized economically [3]. A recent study concludes that the maximum global wind energy potential is dependent on the minimum energy return on investment [15]. The final potential is the implementation potential, which is the economic potential that can be implemented within a certain timeframe, considering institutional constraints and incentives [16]. On the local scale, the feasible wind energy potential was assessed in southwestern Germany [17].

In many countries, economic and implementation constraints limit wind turbine expansion, although the technical potential would be sufficient to cover large parts of electricity consumption [1]. Therefore, it is important to make wind energy expansion efficient, while at the same time achieving a high level of local acceptance for wind energy.

The wind turbine siting efficiency is often investigated for currently installed wind turbines. For instance, Sağlam [18] evaluated the efficiency of wind power in the United States at a federal state level. In a follow-up study, wind farm efficiency was investigated by the input variables cumulative capacity, wind turbines, and wind power density. The output variables were generated electricity, value of production, and homes powered [19].

After the lifetime of a wind turbine ends, it is necessary to evaluate whether the wind turbine should be closed, modernized, or repowered. The main advantages of repowering are better exploitation of the wind resource, reduction of wind turbine number, and avoidance of new site selection [20]. Furthermore, the acceptance of the local population for wind energy is often higher at locations where wind turbines are already installed [21]. Consequently, repowering is preferable to new wind turbine site selection, provided that the energy yield of the