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Efficiency and effectiveness of global onshore wind energy utilization

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ABSTRACT

The progress of onshore wind expansion varies globally, as often expressed by a country's installed capacity and capacity factor. However, installed capacity and capacity factor do not allow conclusions about how effectively and efficiently countries use their spatially diverse wind potential. It is unknown how far wind energy expansion is and whether the countries use the available potential in the best possible way. Thus, this study aims to quantify and compare the wind potential use effectiveness and efficiency for the 40 countries with the highest installed capacity in 2021. A global wind turbine site dataset and the wind farm potential index were used for estimating the suitability of current wind turbine sites. The wind potential use efficiency was calculated by comparing the (1) distributions of the wind farm potential index at wind turbine sites with (2) distributions of the wind farm potential index of the countries as a whole by the Kolmogorov-Smirnov test statistic. The capacity-to-suitable-area ratio defined the wind potential use effectiveness. The results reveal that 81.9% of the global onshore wind turbine fleet operates at suitable sites. Simultaneous occurrences of high effectiveness and efficiency are not given in any country: China, Brazil, and Italy use their wind potential more efficiently than many other countries. The USA and India adequately consider the wind resource efficiency for wind turbine siting. Germany has the highest effectiveness despite low efficiency. The results reveal how critical it is to quantify the progress of wind energy expansion based on the effectiveness and efficiency, not only the installed capacity and capacity factor.

1. Introduction

Achieving the goals set by the Paris Climate Agreement to mitigate global climate change requires the substitution of conventional energies for renewables [1]. Wind energy is currently the most relevant renewable energy covering 6.5% of worldwide electricity generation in 2021 [2]. The globally installed onshore wind capacity (*IC*) is on the rise. In 2010, *IC* was only 178 GW, but in 2021 it was already 769 GW [3]. The three countries with the highest *IC* in 2021 are China (303 GW), the USA (133 GW), and Germany (56 GW). Besides, the use of wind energy has become increasingly successful over the last decade. The global mean capacity factor (*cf*) increased from 0.22 in 2010 to 0.24 in 2020 [3]. The country-specific *cf* values in 2020 were 0.19 in China, 0.33 in the USA, and 0.22 in Germany.

Effectiveness and efficiency describe the success of wind energy development in a country. "Doing the right things" is known as effectiveness [4]. In contrast, "Doing things right" is an accepted definition of efficiency. Thus, a reasonable explanation of the effectiveness of wind energy use is "installing as many wind turbines as possible to mitigate climate change." In contrast, efficiency is "installing new wind turbines at the most suitable sites."

These definitions imply that *IC* and *cf* can only improperly define and compare the effectiveness and efficiency of wind energy expansion of different countries. The reason is that they do not consider the country's wind potential. Site characteristics determine the wind potential and the success of wind turbine operation. Meteorological and geographical factors strongly influence the turbine site quality [5]. Overall, meteorological, geographical, and technical factors define the wind potential of an area [6]. Thus, the wind potential is spatially highly variable and varies between countries [7].

The meteorological wind potential factors include wind speed and air density, yielding wind power [8]. Wind speed (*U*) drives wind power to a much higher degree than air density [9]. The spatiotemporal variability of *U* is enormous [10]. The highest mean wind speed (*UM*) values occur where the surface roughness is low, e. g., over deserts, near coasts, in the central United States, and southern Argentina [11]. In large areas with low *UM*, exposed sites such as mountain tops may still have high *UM* [12]. Temporally *U* is characterized by annual cycles, seasonal cycles, and long-term trends [13]. Thus, the *U* histogram is often complex, so *UM* is only a rough indicator of wind resource availability [14]. Multi-parameter statistical distributions enable the calculation of wind energy

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Nomenclature

Acronyms

ARG	Argentina
AUS	Australia
AUT	Austria
BEL	Belgium
BGR	Bulgaria
BRA	Brazil
CAN	Canada
CHL	Chile
CHN	China
DEU	Germany
DNK	Denmark
EGY	Egypt
ESP	Spain
FIN	Finland
FRA	France
GBR	Great Britain
GloWiSMo	Global Wind Speed Model
GRC	Greece
HRV	Croatia
H_0	null hypothesis
H_a	alternative hypothesis
IND	India
IRENA	International Renewable Energy Agency
IRL	Ireland
ITA	Italy
JPN	Japan
KOR	South Korea
LTU	Lithuania
MAR	Morocco
Mex	Mexico
NLD	the Netherlands
NOR	Norway
NZL	New Zealand
POL	Poland
PRT	Portugal
ROU	Romania
RUS	Russia
SWE	Sweden
TUR	Turkey
TWN	Taiwan
UKR	Ukraine
URY	Uruguay
USA	United States of America
ZAF	South Africa

Symbols

$\widetilde{DU}$	median distance to urban areas (km)
cf	capacity factor
D	Kolmogorov-Smirnov-statistic
DU	distance to urban areas (km)
ES_{GPI}	geographical potential use effectiveness
ES_{RPI}	wind resource use effectiveness
ES_{WPI}	wind potential use effectiveness
EY_{GPI}	geographical potential use efficiency
EY_{RPI}	wind resource use efficiency
EY_{WPI}	wind potential use efficiency
$F(WPI_T)$	cumulative distribution of *WPI* at wind turbine sites
$G(WPI_C)$	cumulative distribution of *WPI* in the country
GPI	geographical potential index
IC	installed capacity (GW)
m	sample size of wind turbines in a country
$MSWC$	meteorologically suitable wind capacity (GW)
n	sample size of grid cells in a country
RE	relative elevation (m)
RPI	resource potential index
SA_{GPI}	geographically suitable area (km^2)
SA_{RPI}	meteorologically suitable area (km^2)
SA_{WPI}	suitable area (km^2)
SWC	suitable wind capacity (GW)
U	wind speed (m/s)
UM	mean wind speed (m/s)
WPI	wind farm potential index
z_0	roughness length (m)

yield and *cf* [15]. For bimodal wind speed regimes, using mixture distributions may be necessary [16]. At some sites, non-parametric distributions provide better fits than multi-parameter or mixture distributions [17].

Geographical factors impede or prevent the development of a site for wind turbine operation. Thus, the geographical potential further reduces the meteorological potential [18]. Geographical exclusion criteria are a case-by-case decision [19] since the exclusion of a site may be for legal or practical reasons. Wind turbines near urban areas pose problems due to noise [20] and aesthetics [21]. Wind turbines close to settlements are unpopular. The distances from the nearest residential area differ based on legislation and tolerance of the local population [22]. Wind turbines should intervene as little as possible in ecosystems [23]. Therefore, protected areas are another crucial geographical restriction criterion [24]. For practical reasons, wind turbine operation on inland lakes, wetlands, snow/ice, and permafrost is not feasible [24]. Installation of wind turbines in such areas requires special anchorage and foundation. Slopes are also problematic for wind turbine installation.

The threshold above which wind turbine operators define a site as unsuitable varies. Maximum slope inclinations are up to 15° [25]. Due to wind turbine icing [26] and low air density [25], highly elevated areas are restricted. There are also geographical factors that are not preferred as wind turbine sites, although they do not hinder it. They include cropland and forests since wind turbine in such areas requires land conversion [27]. Accordingly, land cover types such as shrub, bare, or herbaceous are more suitable.

The technical wind potential considers the available technology besides the meteorological and geographical factors. The advancement of wind turbines influences the development of the technical wind potential [28]. It is reflected by rising hub heights, growing rotor diameters, and higher-rated powers of modern wind turbines [29].

Many studies evaluate the national and global meteorological, geographical, and technical wind energy potential [7]. For instance, one study investigated the meteorological potential by analyzing the accuracy and outlier frequency of >12,000 globally distributed wind speed sites [30]. Another study assessed the geographical potential of the USA considering land use restrictions [6]. Due to the different approaches and uncertainties, global estimates of the technical potential have a wide range [31].

The temporal development of *IC* and *cf* is routinely reported [3]. However, studies of the wind potential on the one side and *IC* and *cf* on the other do not allow conclusions about how effectively and efficiently countries use their spatially diverse wind potential. It is unknown how far advanced wind energy expansion is and whether the countries use the available potential in the best possible way.

This study aims to provide information on the current state of national and global onshore wind energy development. The hypothesis is tested that considering wind potential effectiveness and efficiency leads to a different result than considering only *IC* and *cf*. Thus, the goals are to quantify and compare wind potential use effectiveness (ES_{WPI}) and wind potential use efficiency (EY_{WPI}) for the 40 countries with the highest *IC* in 2021. The study distinguishes between meteorological and geographical efficiency and effectiveness, and the meteorological and geographical suitability is determined for current wind turbine sites to quantify the country-wide efficiencies.

2. Material and methods

The estimation of the country-specific efficiency and effectiveness of wind turbine siting comprises the following main steps (1) obtaining wind turbine site data; (2) acquisition of wind turbine siting suitability data; (3) preparation of wind speed and land cover data; (4) determining the suitability of currently installed wind turbines; (5) calculating the wind potential use efficiency of currently installed wind turbines by comparing the site suitability at the occupied area with the rest of the country; and (6) calculating the wind potential use effectiveness by comparing actual installed capacity with the suitable area.

The steps described in the Material and Methods section were performed using the ArcGIS® 10.6 software (Esri, Redlands, CA, USA) and Matlab 2022a software (The MathWorks, Natick, Massachusetts, USA).

2.1. Available data

Different datasets were used to calculate the efficiency and effectiveness of wind turbine siting. The first dataset is a global wind turbine site dataset developed by Dunnet et al. [32]. It comprises the latitude and longitude of 276,617 wind turbines which are summarized as 33,514 wind farms. Even more detailed wind turbine datasets were available for the USA [33] and Germany [34]. They include the operation start year and the explicit coordinates for each wind turbine, which allowed spatiotemporally more precise analyses for the USA and Germany.

The wind farm potential index (*WPI*) [35] was used to quantify the site suitability. The global pattern of *WPI* (2000 m × 2000 m) is presented in Fig. 1, together with wind turbine density in 2020. Good to excellent technical wind potential exists in northwestern Europe, Brazil, China, and the USA. In these regions, the wind resource is high, and geographical accessibility is given. *WPI* integrates the geographical potential index (*GPI*) and resource potential index (*RPI*). The geographical factors integrated into *GPI* are high elevation, permafrost, protected areas, railroads, sloped areas, snow and ice, streets, urban areas, inland water bodies, and wetlands. These factors lead to a site being unsuitable for wind turbine siting. In addition, forests and agriculture limit the site's suitability gradually. The wind resource integrated into *RPI* is equivalent to the potential capacity factor at a site using a typical, modern wind turbine. *WPI* considers both *GPI* and *RPI* evenly.

The Global Wind Speed Model (GloWiSMo) is available at a horizontal resolution of 250 m × 250 m [11]. GloWiSMo was developed by a machine learning algorithm. The target variables were wind speed L-moments (e.g., *UM*) from 6146 wind speed time series. The predictors were *UM* from reanalysis data available on a 0.25° × 0.25° grid representing the large-scale wind field. Additionally, eleven predictors were derived from land cover and digital elevation models. The mean absolute error of GloWiSMo for *UM* is 0.53 m/s.

In addition, a global land cover dataset available at a horizontal resolution of 100 m × 100 m from the Copernicus Global Land Service was used [36]. It consists of 23 discrete land cover classes.

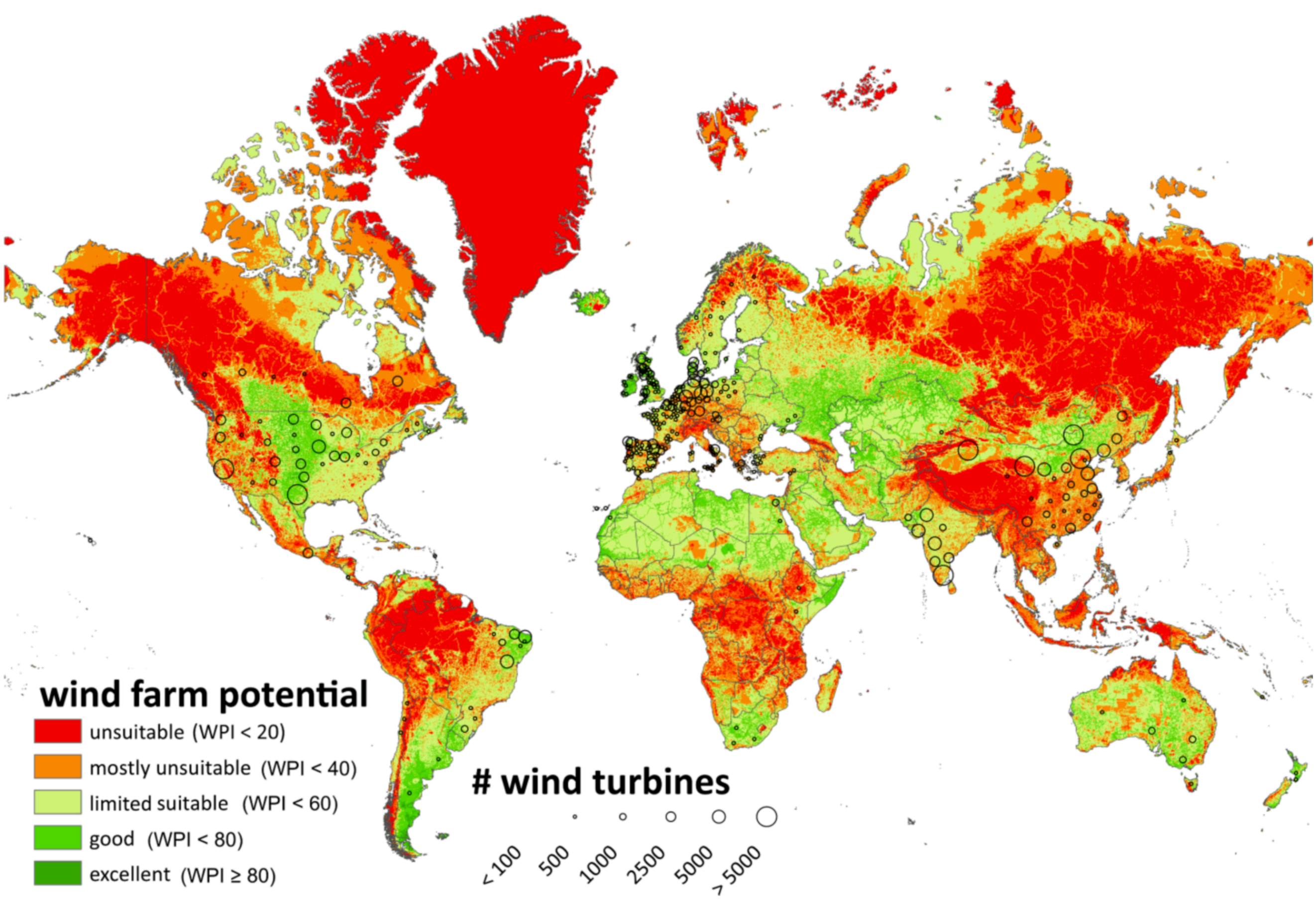

Fig. 1. Wind farm potential index (*WPI*) [35] and number of wind turbines [32] per administrative unit.

2.2. Evaluation of site suitability

The site suitability was determined at the wind turbine locations by *WPI*. A wind turbine site is considered suitable when $WPI \geq 40$. This threshold means that a wind turbine site is (1) limited suitable, (2) good, or (3) excellent. The installed capacities associated with the suitable wind turbines were determined for different *UM* and land cover classes yielding the suitable wind capacity (*SWC*).

The selected *UM* classes from GloWiSMo are $UM < 6$ m/s, $6 \leq UM \leq 8$, and $UM > 8$ m/s. The land cover classes are cropland, herbaceous, forest, bare, shrubs, and urban. They were summarized from the 23 classes of the land cover dataset.

Besides, the meteorological suitability was determined. A wind turbine site with $RPI \geq 20$ (equivalent to $cf \geq 0.20$) is considered meteorologically suitable [37]. The meteorologically suitable wind capacity (*MSWC*) was determined for different terrain and types of surface roughness. The orography classes were defined by the relative elevation within circles with radii of 25 km (*RE*) [11]. They include sheltered ($RE < -20$ m), flat (-20 m $\leq RE \leq 20$ m), and exposed ($RE > 20$ m) terrain. The surface roughness conditions are based on the effective roughness length within circles with a radius of 25 km (z_0) [11]. They were grouped in low ($z_0 < 0.40$ m), medium (0.40 m $\leq z_0 \leq$ 0.65 m), and rough surface ($z_0 > 0.65$ m). The three *RE* and z_0 classes were selected for a clear and easy-to-understand presentation and according to the distribution of the *RE* and z_0 values at the wind turbine sites. Each class should contain a relevant number of wind turbines.

In addition, the geographical suitability was estimated. A site is considered geographically suitable when $GPI \geq 20$.

2.3. Evaluation of distance to urban areas

The distance to urban areas (*DU*) [38] was calculated based on the wind turbine fleet and the global land cover dataset country-specific. The urban areas from the land cover dataset are available as raster. For *DU* estimation, they were converted to polygons using ArcGIS software. Next, the distance between each wind turbine site and the nearest urban area was measured.

2.4. Evaluation of efficiency

The efficiency evaluation was performed for the 40 countries with $IC > 500$ MW in 2021 available from the International Renewable Energy Agency (IRENA) [3]. The first step for efficiency evaluation was to extract the continuous *WPI* values at the wind turbine sites in a country (sample size *m*) and the *WPI* values in the entire country (sample size *n*). Then, the *WPI* probabilities were transformed into cumulative probabilities. It yields the cumulative *WPI* distribution at wind turbine sites $F(WPI_T)$ and the cumulative *WPI* distribution in the country area $G(WPI_C)$.

An efficient wind turbine siting is defined by the deviation between $G(WPI_C)$ and $F(WPI_T)$. A country uses its resource better the higher the differences are. For quantification, the two-sample Kolmogorov-Smirnov test statistic (*D*) was used. Generally, *D* is used to test the null hypothesis (H_0) that two samples come from a population with the same distribution [39]. The alternative hypothesis (H_a) is that they are from different distributions. The reasons for using the Kolmogorov-Smirnov statistic are that: it (1) considers the entire distribution of *WPI* values, (2) is sensitive near the center of the distribution, and (3) is a well-known metric in the research field (e. g., for goodness-of-fit evaluation of wind speed distributions). Here, *D* is used as the equivalent of the efficiency of wind turbine siting:

$$EY_{WPI} = D = max[G(WPI_C) - F(WPI_T)] \quad (1)$$

The wind resource use efficiency was calculated in a similar way, but instead of *WPI*, the *RPI* distributions at the wind turbine sites and the countries as a whole were used (EY_{RPI}):

$$EY_{RPI} = D = max[G(RPI_C) - F(RPI_T)] \quad (2)$$

Additionally, the geographical potential use efficiency was calculated using the *GPI* distribution at the wind turbine sites and in the countries as a whole (EY_{GPI}):

$$EY_{GPI} = D = max[G(GPI_C) - F(GPI_T)] \quad (3)$$

The efficiency evaluations were also performed for the USA and Germany at the state levels. In these cases, the *WPI*, *RPI*, and *GPI* distributions were used for the states instead of the countries. The efficiencies for these countries were also estimated annually since the wind turbine fleet data of the USA and Germany provide the years of operation start.

2.5. Evaluation of effectiveness

For estimation of the wind potential use effectiveness, the suitable areas (SA_{WPI}) for wind turbine siting were calculated first country-specific. The areas where $WPI \geq 40$ are defined as SA_{WPI}. Then, the ratio between SA_{WPI} and *IC* was used to estimate ES_{WPI}:

$$ES_{WPI} = \frac{IC}{SA_{WPI}} \quad (4)$$

The wind resource use effectiveness (ES_{RPI}) requires the areas where $RPI \geq 20$ yielding the meteorologically suitable area (SA_{RPI}). Then, ES_{RPI} was calculated by

$$ES_{RPI} = \frac{IC}{SA_{RPI}}. \quad (5)$$

Similarly, the geographically suitable areas (SA_{GPI}) were defined as $GPI \geq 20$ to calculate the geographical potential use effectiveness (ES_{GPI}):

$$ES_{GPI} = \frac{IC}{SA_{GPI}} \quad (6)$$

3. Results and discussion

This section presents results on the suitability of wind turbine sites and the impacts of siting approaches on developing national turbine fleets. A global comparison of wind potential use efficiency and effectiveness is presented. The USA and Germany were chosen as cases to illustrate definite and concrete results because of their large *IC* and great wind potentials.

3.1. Suitability of wind turbine sites

The share of suitable and unsuitable wind capacity is presented as an Alluvial diagram, including the components continent, *UM*, and land cover in Fig. 2a. The majority (81.9%) of the global onshore wind turbine fleet is installed at suitable locations. The combination of cropland and *UM* between 6 and 8 m/s contains the highest installed capacity ($IC = 279.1$ GW) worldwide. Sites with this combination of characteristics are most often (share of $SWC = 86.5\%$) suitable for onshore wind turbines. Considering also the continent, the combination with the most suitable wind capacity ($SWC = 90.7$ GW) occurs in North America, where *UM* is between 6 and 8 m/s and the land cover type is cropland. The combination with the most unsuitable wind capacity (27.8 GW) exists in Asia, where $UM < 6$ m/s and the land cover type is cropland.

The most relevant individual factor for the suitability of a site is *UM*. Regardless of continent and land cover, 98.3% of all global sites with $UM > 8$ m/s are suitable. Only 8.4% of the global installed capacity is sited where $UM > 8.0$ m/s. The highest installed capacity where $UM > 8$ m/s is in Asia ($IC = 28.5$ GW), corresponding to a relative share of only 8.2%. In Oceania and Africa, approximately a quarter of the wind turbine fleet is installed where $UM > 8$ m/s.

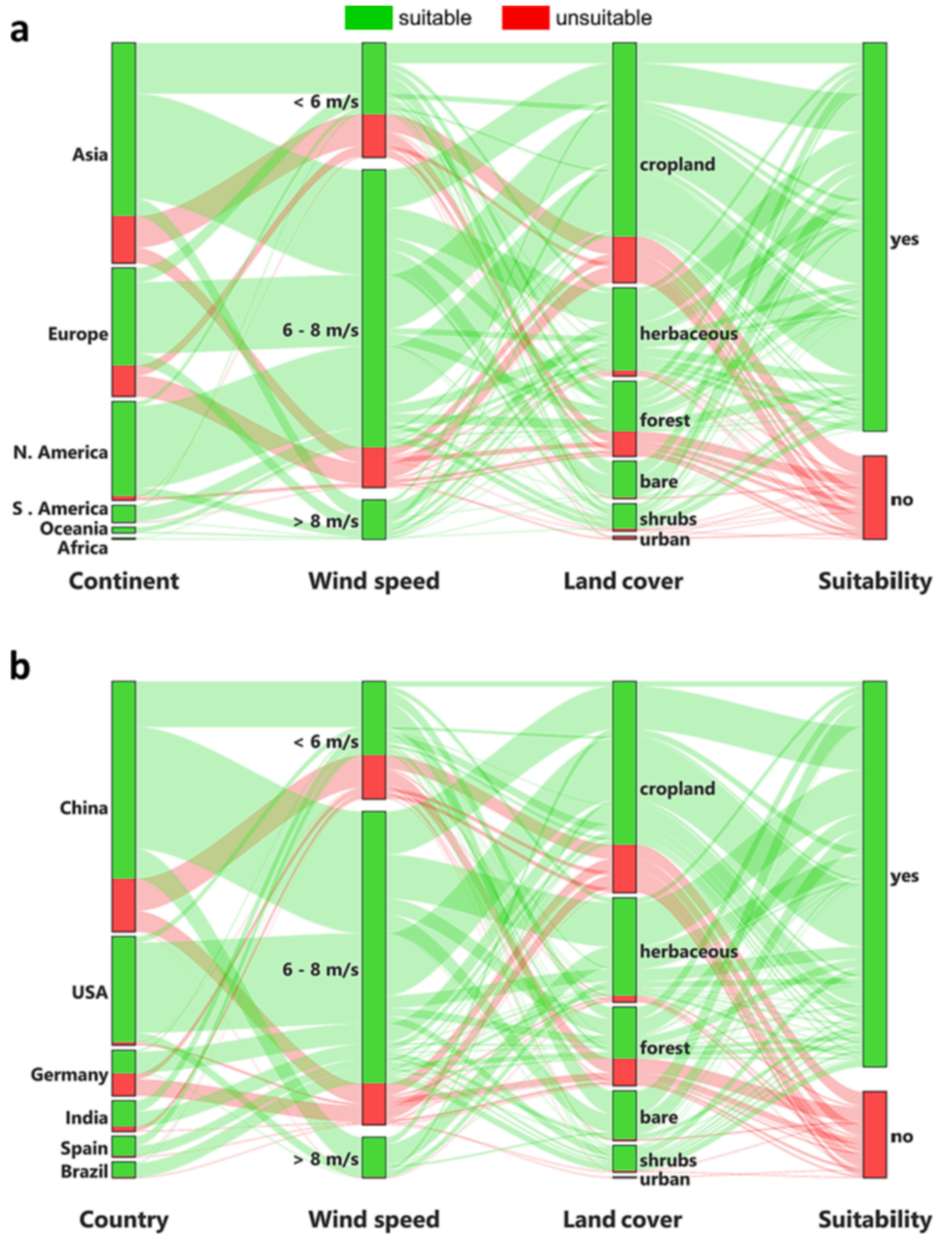

Fig. 2. Share of suitable (*SWC*) and unsuitable wind capacity according to the wind farm potential index (*WPI*) classified in mean wind speed (*UM*) and land cover type for a) continents, and b) the six countries with highest installed capacity (*IC*).

The land cover types, bare, shrubs, and herbaceous, result in suitable areas. A very high share (share of $SWC = 93.1\%$) of global wind capacity installed on one of these land covers is suitable for wind turbines. Consequently, the combination of land cover types shrub, bare, or herbaceous with wind speed $UM > 8$ m/s almost always (98.7%) results in a site being suitable for onshore wind turbines.

The Alluvial diagram in Fig. 2b also presents the share of suitable and unsuitable wind capacity for *UM* and land cover types but for the six countries with the highest *IC* instead of the continents. In China, 78.2% of the wind capacity is at suitable sites. A total wind capacity of 53.2 GW with a combination of *UM* between 6 and 8 m/s and land cover type herbaceous is suitable for wind turbines. In contrast, the most wind capacity in unsuitable areas occurs when $UM < 6$ m/s and the land cover type is forest.

The USA has the highest share of suitable wind capacity, with 95.7%. By far, most of this suitable capacity (75.4 GW) exists at sites where *UM* is between 6 and 8 m/s and the land cover type is cropland. There is no combination of *UM* and land cover containing an unsuitable capacity of >2 GW.

Germany has the lowest share of wind capacity at suitable sites, with only 52.3%. The combination of *UM* between 6 and 8 m/s and cropland contains about 66% of Germany's wind capacity, and 59.4% of this capacity is identified as suitable.

In India, the share of wind capacity at suitable sites is 82.0%. The highest *IC* (15.8 GW) in India is located on cropland where $UM < 6$ m/s. About 35% of this capacity is defined as unsuitable.

Spain's wind capacity is most often (90.3%) at suitable sites. Unlike the other countries, a high share of the Spanish wind capacity is installed in forests, and many of the forest sites prove suitable for wind energy use.

The wind turbine fleet of Brazil has a high site suitability, with 92.7% of the wind turbines at suitable sites. There, most of the suitable wind capacity exists in shrubs where *UM* is between 6 and 8 m/s.

The meteorological suitability for wind turbines is presented as an Alluvial diagram, including the components continent, orography, and surface roughness in Fig. 3a. The global onshore wind capacity is usually

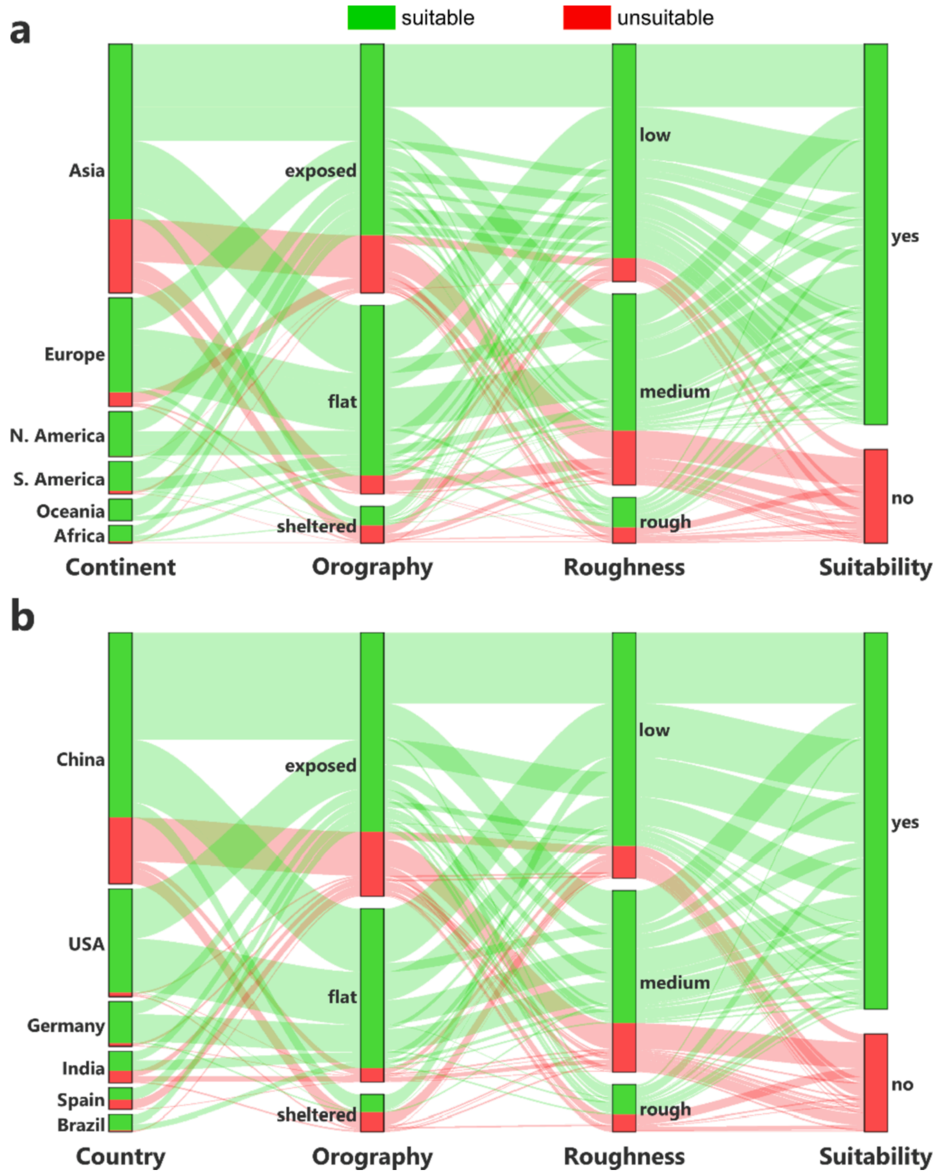

Fig. 3. Share of meteorologically suitable (*MSWC*) and unsuitable wind capacity according to the resource potential index (*RPI*) classified in orography and surface roughness for a) continents, and b) the six countries with highest installed capacity (*IC*).

(share of *MSWC* = 79.4%) installed at meteorologically suitable sites. Most installed wind capacity (*MSWC* = 180.0 GW) occurs in exposed terrain and low surface roughness areas. This combination frequently (share of *MSWC* = 91.8%) results in meteorological suitability. Considering all three components of the Alluvial diagram, the wind capacity installed in Asia in exposed terrain and low surface roughness contains the most suitable wind capacity, with *MSWC* = 98.1 GW. The most unsuitable wind capacity (*MSWC* = 43.1 GW) exists in Asia on exposed terrain and medium surface roughness.

The flat terrain and low surface roughness have the highest shares of *MSWC*, with ≈ 89%. Combining both factors results in an *MSWC* share of 94.0%. In Europe and North America, wind turbine sites with this combination have *MSWC* shares of about 99%. It is somewhat surprising that the share of suitable areas for exposed terrain is lower than for flat orography. One reason could be that windy areas near coasts often have less orography and are flat [40]. High exposure is necessary when the large-scale wind resource is weak.

A sheltered orography is the most unfavorable single factor considering meteorological suitability leading to the global *MSWC* share being 50.9%. Combining the properties of sheltered orography and rough surface is even worse since only 29.3% of the wind capacity sited in such areas is meteorologically suitable. In Asia, there is no wind capacity meteorologically suitable under these conditions.

Across all orography and surface roughness types, the highest *MSWC* shares exist in North America and Oceania. In contrast, Asia has a minor share of meteorologically suitable wind capacity, with 70.3%. In Europe, South America, and Africa, the *MSWC* share is about 87%.

In China, 74.1% of the wind capacity is at meteorologically suitable sites (Fig. 3b). The highest *MSWC* (85.5 GW) was estimated for exposed terrain and low surface roughness. In contrast, exposed terrain and medium surface roughness result in the highest unsuitable wind capacity at 30.8 GW.

Nearly all (share of *MSWC* = 95.5%) of the wind capacity in the USA is in areas with a high enough wind resource for wind turbine operation. High *MSWC* values were found for different combinations of orography and surface roughness. Only sites with sheltered orography or rough surface are less often suitable.

Most of Germany's wind capacity (share of *MSWC* = 91.3%) operates under meteorologically suitable conditions. The highest *MSWC* (26.3 GW) was identified for sites with flat exposure and medium surface roughness conditions.

The share of meteorologically suitable wind capacity in India is 61.0%. Most meteorologically suitable wind capacity exists where the surface roughness type is low, and the terrain is flat ($MSCW = 8.3$ GW) or exposed ($MSCW = 7.1$ GW). In contrast, a medium surface roughness often results in unsuitable wind capacity.

In Spain, the share of *MSCW* is 53.5%, and an *IC* share of 92.0% is at exposed sites. The combination of exposed terrain and medium surface roughness yields the highest *MSWC* at 8.7 GW.

The *MSCW* share in Brazil is 88.8%. The highest *MSWC* value at 7.0 GW exists for exposed terrain but rough surfaces.

The frequencies of *DU* are shown for the ten countries with the highest *IC* in Fig. 4. The highest median *DU* ($\widetilde{DU}$) exists in India, with 10.6 km. Wind turbines are also relatively far from urban areas in Brazil and the USA. In contrast, the wind turbines in Europe are often close to urban areas, with $\widetilde{DU}$ being 1.1 km in Germany and 1.4 km in France and GBR. Intermediate $\widetilde{DU}$ (≈ 3.5 km) occurs in China, Spain, and Canada.

The *DU* values represent the distance to settlements of currently operating wind turbines. They also indicate whether the geographical potential requires installing future wind turbines close to urban areas. It is especially true if the *DU* distribution has only a minor portion in the upper range. For instance, in Germany, only 10.2% of the installed wind capacity is >2 km from the nearest urban area, and in France, this applies to only 24.2% of the total wind capacity. The situation is different in India and Brazil, where the *DU* distribution is wide and high values are frequent.

3.2. Efficiency and effectiveness

The differences between the distributions of WPI_C and WPI_T are critical for calculating wind potential use efficiency. The WPI_C and WPI_T distributions are presented in Fig. 5a and 5b for China since it has the highest *IC*.

The most frequent WPI_C class (class width: 10) is 40, whereas $WPI_T = 50$ is the most common. The WPI_T distribution is left-skewed, indicating many high and a few low WPI_T values. In contrast, WPI_C values to the right and left of the median WPI_C are relatively evenly distributed. The distinctive differences between WPI_C and WPI_T frequencies indicate that in China, wind turbine sites generally have much greater wind potential than the average wind potential in the country.

The courses of $G(WPI_C)$ and $F(WPI_T)$ are displayed in Fig. 5c. High $G(WPI_C)$ already occurs at $WPI < 0$. The median WPI_C is 28, whereas the median WPI_T is 53. More than a third of $WPI_T \geq 60$, although only 5.6% of the country's area falls within $WPI_C \geq 60$. The maximum difference between $G(WPI_C)$ and $F(WPI_T)$, equivalent to EY_{WPI}, is 0.49.

The ES_{WPI} value results from *IC* and *SA* (Fig. 5d). The *SA* value in China is 2722736 km^2, and *IC* is 303 GW. The ES_{WPI} value of 0.11 indicates that there are still numerous suitable wind turbine sites in China. Despite high wind energy expansion, the wind potential has yet to be fully exploited.

An international comparison between EY_{WPI}, EY_{RPI}, and EY_{GPI}, is shown in Fig. 6. The H_0 hypothesis is rejected for all countries i.e. WPI_T and WPI_C have different distributions (significance level 0.05). The substantial differences between the countries illustrate that onshore wind energy expansion proceeds differently worldwide. Some countries share similar efficiency characteristics.

A cluster of the European countries Germany (DEU), Great Britain (GBR), Portugal (PRT), Denmark (DNK), Ireland (IRL), and Belgium (BEL) shares low EY_{RPI} (≤ 0.30), EY_{GPI} (≤ 0.15), and EY_{WPI} (≤ 0.20) values. It is crucial to consider that GBR, DNK, and IRL have abundant wind resources [11]. Thus, wind potential in site selection may be less emphasized, resulting in low efficiencies. Another reason for low wind resource use efficiency may be frequent misestimating of wind resources due to missing or inaccurate measurements [30] and modeling [7]. Despite the similarities in efficiency, there are relevant differences in the effectiveness of wind potential use. The highest ES_{WPI} value of 0.48 occurs in DEU, indicating that onshore wind energy expansion is advanced. However, the low efficiency of $EY_{WPI} = 0.20$ suggests that many of the remaining candidate wind turbine sites provide better wind potential than currently used sites.

The USA, India (IND), Spain (ESP), France (FRA), Sweden (SWE), Mexico (MEX), and Austria (AUT) belong to a second cluster. They use the wind resource more efficiently ($EY_{RPI} \geq 0.40$) than the countries of the first cluster. However, the geographical potential ($0.15 \leq EY_{GPI} \leq 0.30$) is only slightly better exploited. Thus, wind resource availability may be the decisive criterion for wind turbine siting. The EY_{WPI} values are about 0.40. Wind energy expansion is often not yet far advanced concerning the available potential. For the USA, ES_{WPI} equals 0.02. A substantially higher effectiveness exists in Austria, with $ES_{WPI} = 0.28$.

A third cluster includes China (CHN), Italy (ITA), Australia (AUS), and Norway (NOR). In these countries, EY_{RPI} ($0.30 \leq EY_{RPI} \leq 0.60$) and EY_{GPI} ($0.30 \leq EY_{GPI} \leq 0.60$) are at similar levels. Thus, wind resource availability and geographical criteria are similarly weighted in wind turbine siting. EY_{GPI} is higher than in the other two clusters, but EY_{RPI} is

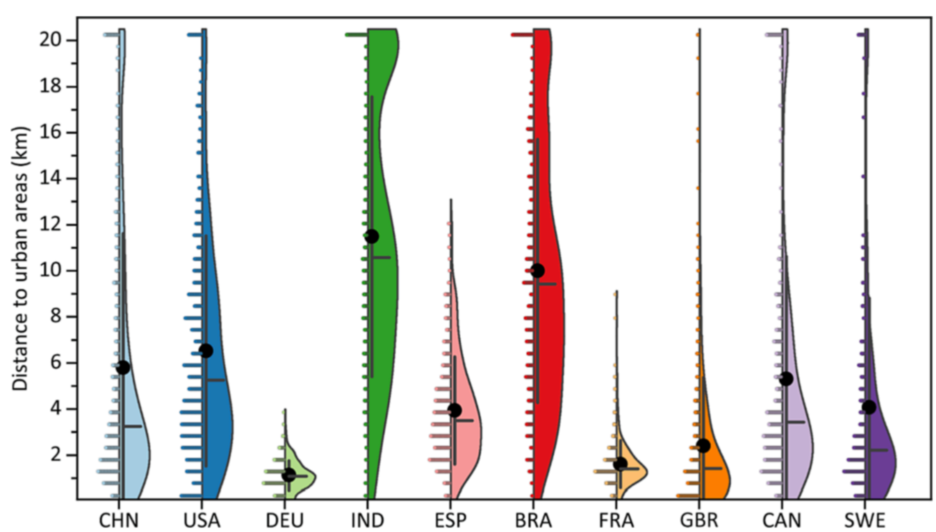

Fig. 4. Frequencies of the distance to urban areas (*DU*) for China (CHN), the United States of America (USA), Germany (DEU), India (IND), Spain (ESP), Brazil (BRA), France (FRA), Great Britain (GBR), Canada (CAN), and Sweden (SWE). The half-violin plot consists of a dot plot on the left and a violin plot on the right. The black dots represent the mean and the grey vertical lines the median.

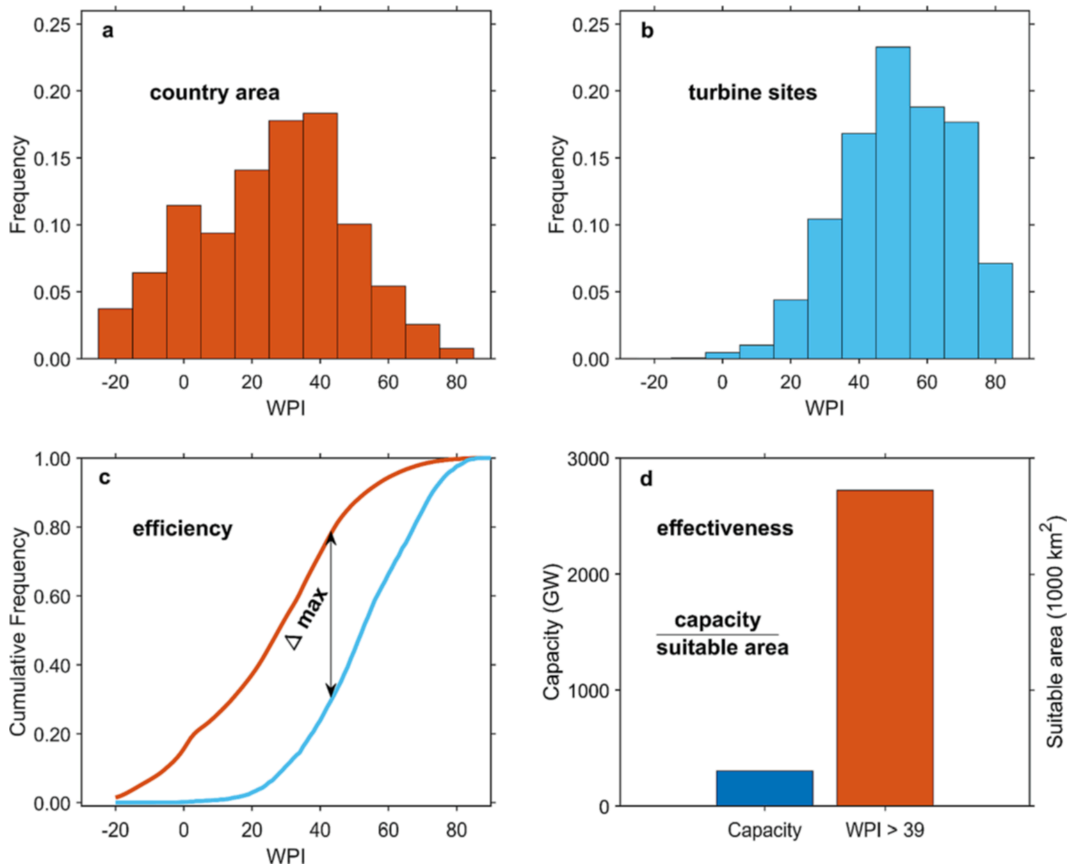

Fig. 5. Efficiency and effectiveness of China's wind turbine fleet represented by a) the distribution of the wind farm potential Index (*WPI*) in the country area (WPI_C), b) the distribution of *WPI* at the wind turbine sites (WPI_T), c) the cumulative distribution functions of *WPI* in the country area ($G(WPI_C)$) and at the wind turbine sites ($F(WPI_T)$), and d) the ratio between installed capacity (*IC*) and suitable area (*SA*).

lower than in the second cluster. Due to the adequate consideration of EY_{RPI} and EY_{GPI}, the EY_{WPI} values ($EY_{WPI} \approx 0.50$) are highest in this cluster. The ES_{WPI} values of China and Italy (0.16) are relatively high in international comparison. In contrast, wind energy expansion in AUS and NOR has not yet made much progress, with $ES_{WPI} \leq 0.03$.

Some countries do not belong to any cluster and stand solitary. In Brazil, wind resource use efficiency ($EY_{RPI} = 0.84$) and geographical potential use efficiency ($EY_{GPI} = 0.47$) are high, yielding $EY_{WPI} = 0.65$. However, ES_{WPI} is only 0.04. Wind energy expansion is even less advanced in Canada, with $ES_{WPI} = 0.002$. However, the operating wind turbines are in meteorologically ($EY_{RPI} = 0.44$) and geographically ($EY_{GPI} = 0.75$) suitable areas. Although the highest EY_{WPI} value was calculated for Egypt ($EY_{WPI} = 0.80$), *IC* is low at 1.6 GW. Overall, the increased efficiencies of countries such as Egypt, Russia, New Zealand, and Argentina demonstrate that efficient wind turbine siting at low *IC* appears more feasible.

3.3. Comparison of siting efficiency and effectiveness in Germany and in the USA

The operating wind turbines in the USA and Germany in 2021 are displayed in Fig. 7. Germany's more effective use of wind energy reflects in the spatial wind turbine distribution. Germany has a substantially higher wind turbine density. Large areas in the USA virtually contain no wind turbines, especially in the Southeast. In Germany, wind turbines are ubiquitous. In the USA, most wind turbines are in the middle (e. g., Texas, Iowa), where surface roughness is low. In Germany, the focus of wind turbines is in the northwest, near the coast.

Although the wind energy expansion in the USA is worse than in Germany in terms of potential, the wind turbine siting in the USA is more efficient. The vast majority of wind turbines in the USA (97.3%) are suitable, according to *WPI*, but only two-thirds of Germany's wind turbines are suitably sited. The EY_{WPI} values also differ within both countries at the federal-state level. In the state of Idaho, EY_{WPI} is 0.70, and in North Dakota, EY_{WPI} is 0.06. In Germany, EY_{WPI} values are more evenly distributed, which may be due to the smaller area of the country. The EY_{WPI} values range between 0.15 in Mecklenburg-Western Pomerania and 0.52 in Hamburg.

The wind potential use efficiency varies. Due to evolving regulatory requirements, preferences, or decreasing number of available sites, EY_{WPI} may change. The development of EY_{WPI}, EY_{RPI}, and EY_{GPI} between 2000 and 2021 is shown for the USA in Fig. 8a. The 5-year moving averages are used instead of annual values to smooth the influence of variations of annually newly added wind energy capacities on EY_{WPI}, EY_{RPI}, and EY_{GPI}. In the USA, EY_{WPI} peaked in 2000 being 0.60. Until 2011 EY_{WPI} decreased, reaching its minimum of 0.44. Subsequently, EY_{WPI} increased again in the last few years and is at a similar level as in the beginning. The decrease in EY_{WPI} around 2011 is mainly due to lower EY_{GPI} values. In contrast, EY_{RPI} peaked in the last four years. The results suggest that the USA more emphasized wind resource use efficiency in wind turbine deployment in recent years to the detriment of geographical potential use efficiency.

In Germany, the courses of EY_{WPI}, EY_{RPI}, and EY_{GPI} between 2000 and 2021 differ fundamentally from the results of the USA (Fig. 8b). The wind potential use efficiency increased steadily from 2000 to 2021. The reason for the EY_{WPI} development is EY_{GPI}. In 2000, EY_{GPI} was 0.22 but rose to 0.36 in 2021. The increase in EY_{GPI} is by stricter legislation concerning distance to settlements. Increasing attention to geographical efficiency has been at the expense of meteorological efficiency. The EY_{RPI} values decreased from 0.41 in 2001 to 0.30 in 2016. It slightly

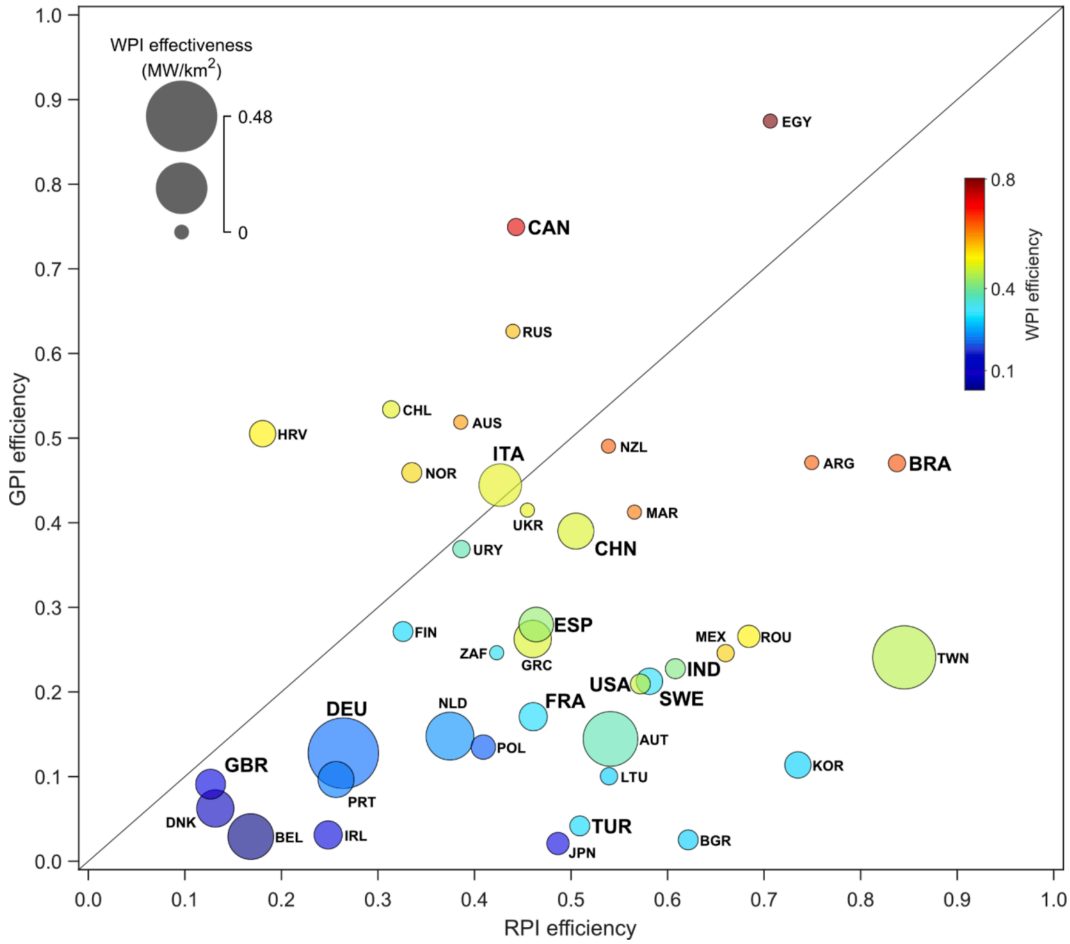

Fig. 6. International comparison of the wind potential use efficiency (EY_{WPI}), the wind resource use efficiency (EY_{RPI}), the geographical potential use efficiency (EY_{GPI}) efficiency, and the wind potential use effectiveness (ES_{WPI}). The 40 countries with the highest installed capacity (IC) in 2021 are included. The abbreviations for the countries are provided in the Nomenclature.

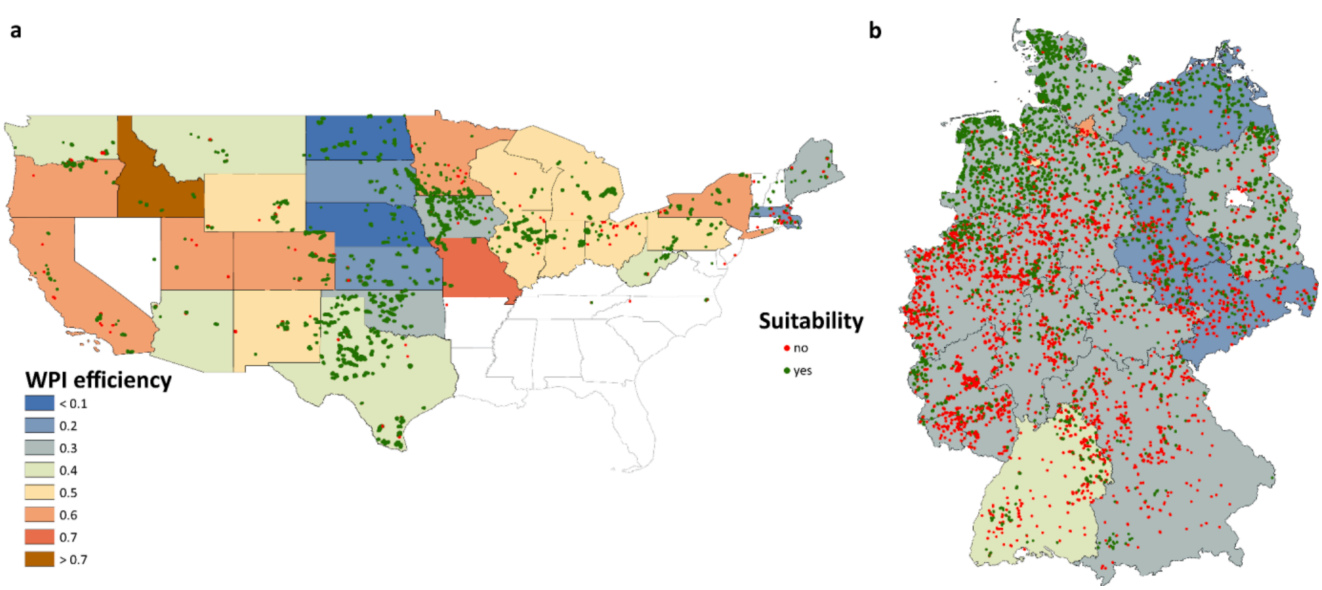

Fig. 7. Suitability of onshore wind turbine sites and wind potential use efficiency (EY_{WPI}) in a) the USA and b) Germany.

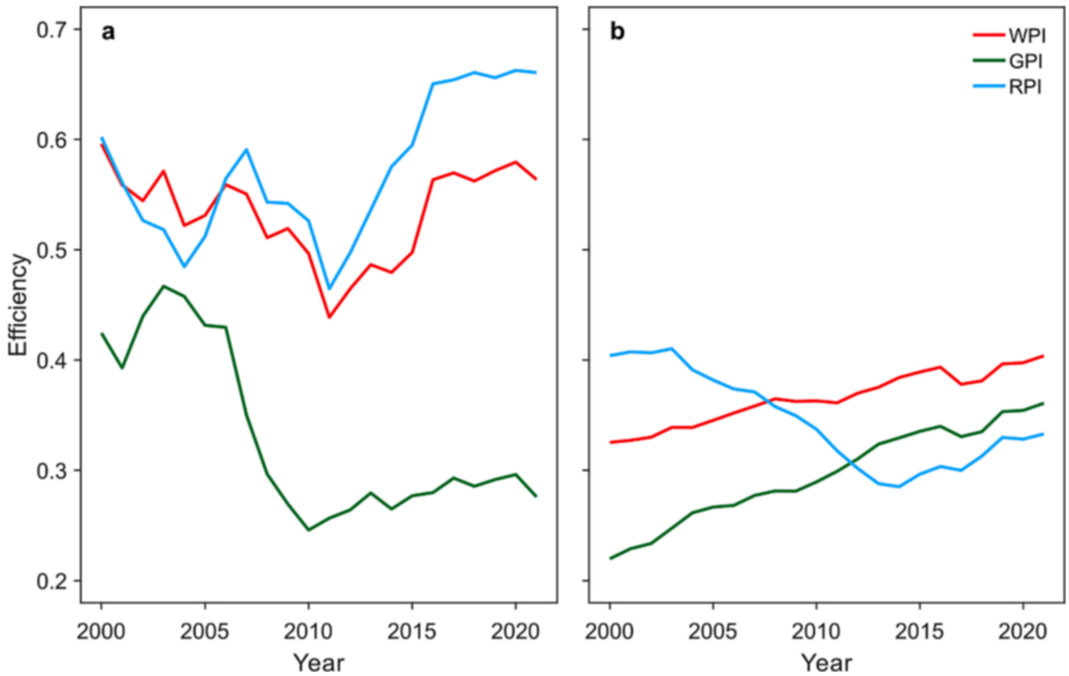

Fig. 8. Development of wind potential use efficiency (EY_{WPI}), geographical potential use efficiency (EY_{GPI}), and wind resource use efficiency (EY_{RPI}) in 2000–2021 of newly installed wind turbines (5-yr moving mean) in a) the USA and b) Germany.

recovered in recent years, with $EY_{RPI} = 0.33$ in 2021.

4. Conclusions

Most (81.9%) of the global onshore wind turbine fleet operates at suitable sites. However, the results revealed that simultaneous high wind potential use efficiency and effectiveness rarely occur. While China ($EY_{WPI} = 0.49$), Brazil ($EY_{WPI} = 0.65$), and Italy ($EY_{WPI} = 0.49$) use their wind potential efficiently, Germany has the highest wind potential use effectiveness ($ES_{WPI} = 0.48$). Besides, the countries consider wind resources and geographical potential differently. For instance, the USA ($EY_{RPI} = 0.57$) and India ($EY_{RPI} = 0.61$) emphasize more on wind resource efficiency in wind turbine siting.

An important conclusion from these results is that installed capacity is an insufficient criterion to assess the progress of wind energy expansion. Wind potential use efficiency and effectiveness, as introduced in this investigation, allow a more precise and differentiated assessment of the wind energy expansion status. Thus, it is recommend adding wind potential use efficiency and effectiveness in future wind energy reports. They enable better management of the country's wind energy development and reduce current shortcomings.

The world has much room for improvement to exploit the climate change mitigation potential provided by wind. Besides, in many countries, the installed wind capacity is so low that they were not considered in the current study. For instance, only three African countries have an installed capacity of $>$ 500 MW, although Africa has enormous wind potential [41]. In these cases, a boost in effectiveness is urgently needed.

This study is intended to provide a global overview of wind potential use efficiency and effectiveness. Wind energy development is often managed and influenced at lower administrative levels. Another limitation is that only one renewable resource (onshore wind) was considered. Besides, many drivers influence efficient and effective wind potential use, including meteorological, geographical, social, economic, and political reasons. This study does not emphasize which of these reasons drive wind potential use efficiency and effectiveness. Based on these limitations, future regional multi-disciplinary research considering all relevant renewables (solar, offshore wind) is required to quantify the contribution of each factor to the efficiency and effectiveness of wind energy development. The methods introduced in this study can serve as a basis for it.

CRediT authorship contribution statement

Christopher Jung: Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – original draft. **Dirk Schindler:** Resources, Validation, Supervision, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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