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Historical wind deployment and implications for energy system models

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ABSTRACT

A critical parameter in modeling studies of future decarbonized energy systems is the potential future capacity for onshore wind power. Wind power potential in energy system models is subject to assumptions regarding: (i) constraints on land availability for wind deployment; (ii) how densely wind turbines may be placed over larger areas, and (iii) allocation of capacity with respect to wind speed. By analyzing comprehensive databases of wind turbine locations and other GIS data in eleven countries and seventeen states in Australia, Canada, and the US; all with high penetration levels of wind power, we find that: i) large wind turbines are installed on most land types, even protected areas and land areas with high population density; ii) it is not uncommon with a deployment density up to 0.5 MW/km^2 on municipality or county level, with rare outlier municipalities reaching up to 1.5 MW/km^2 installed capacity; and iii) wind power has historically been allocated to relatively windy sites with average wind speed above 6 m/s. In many cases, allocation methods used in energy system models do not consistently reflect actual installations. For instance, we find no evidence of concentration of installations at the windiest sites, as is frequently assumed in energy system models. We conclude that assumptions made in models regarding wind power potentials are poorly reflective of historical installation patterns, and we provide new data to enable assumptions that have a more robust empirical foundation.

1. Introduction

Wind power deployment is a hot political topic due to strong popular sentiments in favor of and against wind power installations. In the academic literature, increased renewable power supply is perceived as a key strategy towards decarbonizing the energy system [1]. However, assumptions made regarding the potential for renewable power differ between energy system models, and strongly influence the results obtained [2]. In particular, onshore wind power potential has been shown to be one of the most influential factors determining the cost-effectiveness of a renewable power system in some regions [3–5]. Since wind power is relatively low-cost and the production is not as strongly tied to certain hours of the day as is solar photovoltaics [4,6], it is often the case that wind power at windy sites is the most cost-effective electricity generation option in the models. Thus, estimates of the available onshore wind power potential is a key issue.

There is a specific body of literature that focuses on onshore wind potential [7–13]. In general, this literature excludes land based on various assumptions regarding suitable sites. Criteria used to exclude land relate to socio-political factors such as proximity to settlements and airports, as well as physical/natural factors such as the exclusion of protected areas and wetlands, which are assumed to render wind power installation unsuitable (see Ref. [14] for a comprehensive overview). In the past, energy system models used resource estimates to simply add a constraint on the total amount of wind power capacity that may be deployed in a region [15,16]. However, in order to account for aspects such as load proximity and production profiles, more recent energy system models add detailed GIS data into the models [17,18] and make the allocation of wind power capacity an endogenous model decision. When allocation of wind power capacity is endogenous, the models use similar exclusion criteria as those made in the resource literature, but most often at a less detailed level. In one sense the wind potential represented in the models may be viewed as the *feasible potential*, as defined in Ref. [14], but without the consideration of economic factors, since these are endogenously determined in energy system models.

Other studies use different methods to identify the physical and socio-economic factors that explain the deployment of wind power. Results from these studies could be used as a basis for assumptions that limit the onshore wind potential in models. Nitsch, Turkovska [19] have shown that, in Denmark and Austria, wind turbines are more likely to be situated on agricultural land than on forest land. They have also found that wind speeds recorded on land with installed wind power are slightly

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higher than the national average. Similar results were found in the US when comparing wind deployment in different states [20]. In Iowa, vicinity to both power lines and highways, as well as good wind conditions, have been found to increase the likelihood of wind deployment [21]. In contrast, in the Czech Republic, wind power is more likely to be deployed in urbanized districts with a coal industry [22]. While some studies have reported a negative correlation between population density and wind deployment [22], Mann et al. [21] have shown that in Iowa a high population density within a 200-km radius of wind turbines is positively correlated with wind deployment. In some regions, wind power has been deployed close to residential areas. Möller [23] found that, already in 2007, more than 50% of the population in northwestern Denmark lived within 2 km of wind turbines. In summary, the empirical literature on historical wind power deployment shows results that are rather inconsistent and diffuse in nature.

Another strand of empirical literature concerns the capacity density of wind farms. In the US the power density of parks has slightly decreased since the year 2000 [24]. Stanley et al. [25] further investigate how the size of wind turbines and distance to infrastructure influences power density of wind farms. They further argue that the area of land used to calculate capacity density is not well defined.

Regarding energy system models that use endogenous allocation of wind power, the potential of wind power is quantified by combining estimates of wind conditions and capacity density, with an assessment of the quantity of land that may be devoted to wind installations. Given that the empirical literature on the social considerations that could underly an assessment of available land for wind power is inconclusive, energy system models have based estimates of the total available land for wind power deployment on *a priori* arguments, i.e., with little or no empirical support for these assumptions. This issue is the principal motivating factor for the current study.

In this study, we investigate how wind power has been deployed historically in countries and states with comparatively high levels of wind power installed. The data used are from Austria, Belgium, Denmark, Finland, France, Estonia, Ireland, Portugal, Germany, Sweden, Uruguay, and from 11 US states and three provinces in each of Australia and Canada. Hereinafter, these countries/states are referred to as *regions*. We compare the assumptions made in some energy system models that endogenously include spatial estimates of the wind potential to the real-life situation and provide some support for future assumptions.

Specifically, the main aim of this paper is to derive empirical data to inform and compare to the assumptions as to wind power deployment made in the energy system models.

2. Data and methods

The following is an overview of the methods and main datasets employed in this paper.

2.1. Framework

Three different considerations influence assessments of wind energy potential in modeling studies with endogenous allocation of wind power: (i) assumptions as to which land types are available for wind exploitation (*constraints on land availability*); (ii) assumptions concerning deployable wind capacity per area of available land (*deployment density*), which includes both the maximum fraction of available land that may be employed for wind farms as well as the power density of wind farms; and (iii) the allocation of capacity with respect to the wind resource (wind speed) on these lands (*allocation with respect to wind speed)*. For an overview of assumptions made in some energy system models, see Table 1 in the Supplementary material.

To find *constraints on land availability*, a GIS-based approach is often applied to estimate the amount of land available for wind power deployment. Land may be excluded for three different reasons; because of its land type, if the land has a protected status, or based on its population density. For instance Schlachtberger et al. [18] exclude urban land, wetlands and protected areas, whereas Bogdanov and Breyer [26] do not exclude any land types from wind deployment. A few studies also exclude wind installations in densely populated areas [5,27].

Table 1
Analyzed regions, penetration rate, wind production per area and quality of data. Data on wind production from Refs. [35,36].

Region	Wind power share of demand	Wind production per area of land (MWh/km^2)	Type of data	Accuracy
California, USA	5%	34	Turbines	Exact location
Colorado, USA	24%	50	Turbines	Exact location
Denmark	58%	379	Turbines	Exact location
Illinois, USA	12%	113	Turbines	Exact location
Iowa, USA	67%	236	Turbines	Exact location
Kansas, USA	58%	113	Turbines	Exact location
Minnesota, USA	18%	57	Turbines	Exact location
North Dakota, USA	63%	76	Turbines	Exact location
Oklahoma, USA	45%	1656	Turbines	Exact location
Oregon, USA	17%	35	Turbines	Exact location
South Dakota, USA	43%	282	Turbines	Exact location
Sweden	17%	62	Turbines	Exact location
Texas, USA	22%	137	Turbines	Exact location
Germany	23%	367	Turbines	Exact location, pre 2016
Alberta, Can	7%	8	Parks	Park
Austria	9%	81	Parks	Park
Estonia	13%	18	Parks	Park
France	8%	63	Parks	Park
Ireland	36%	164	Parks	Park
New South Wales, Aus	7%	7	Parks	Park
Ontario, Can	8%	13	Parks	Park
Portugal	23%	134	Parks	Park
Québec, Can	4%	6	Parks	Park
South Australia, Aus	37%	5	Parks	Park
Victoria, Aus	28%	56	Parks	Park
Belgium	14%	427	Parks	Municipality
Finland	12%	24	Parks	Municipality
Uruguay	31%	31	Parks	Municipality

The *deployment density* refers to capacity that may be installed in a larger region, i.e. of municipality size or larger. The total regional potential wind capacity (in MW), *P*, in energy system models is typically calculated as

$$P = A(1-\varepsilon)d\cdot s$$

where *A* is the total area of the region, ε is the fraction of land deemed unsuitable due to *constraints on land availability*, *d is* the assumed power density in wind parks and *s* is the suitability factor, the fraction of the remaining land assumed to be suitable for wind parks. The *deployment density, D,* estimated in our data is expressed as $D = ds$. MacDonald et al. [27] assume a deployment density between 0.5 MW/km^2 and 2.5 MW/km^2 in the US, Schlachtberger et al. [18] assume 2 MW/km^2 in Europe, whereas another study assumes between 0.3 and 1 MW/km^2 in East Asia [26].

For the assumptions made regarding *allocation with respect to wind speed*, two different approaches are identified: optimization [28], whereby the windiest sites tend to be used; and heuristics, whereby wind power is allocated to sites with varying wind speeds according to an exogenous distribution. The heuristics used in the models vary, although all heuristic approaches allocate a predefined fraction of the installed capacity over a larger set of wind sites. For instance, Bogdanov and Breyer [26] assume that 60% of the wind turbines are placed on the 20% windiest sites in each region, whereas Schlachtberger et al. [18] assume that wind power is deployed in proportion to the capacity factor, such that some wind power is also allocated to poor wind sites.

2.2. Data

As the main focus of this paper is to inform models analyzing future deployment of wind power, we target our analysis at regions that either have a large proportion of electricity demand supplied by wind power or where wind power is already densely deployed. How these regions have developed so far may tell us something about regions that will deploy wind power in the future. In addition, we are constrained to use regions where high-quality data of turbine locations are available. With the ongoing trend towards larger wind turbines, we focus most analysis on relatively modern wind turbines larger than 1 MW since the siting of these larger turbines is likely more representative of future turbines.

For the analysis we use two different kinds of datasets of wind power installations, one with exact turbine locations and the other with locations of wind farms and smaller turbine groups. The turbine datasets provide the exact location, capacity, installation year and often rotor diameter for each wind turbine for the US [29], Denmark [30], Sweden [31] and Germany [32]. When compared with the cumulative installed wind power capacity obtained from WindEurope [33], we observe that the turbine datasets have virtually 100% coverage relative to the total installed capacity in 2020 for all regions, with the exception of Germany where the coverage for onshore WP is approximately 70%. The lower coverage for Germany can be explained in part by the fact that the German data are from 2015, which means that recently installed capacity is not included. Considering only the total installed capacity at the end of 2015, this data set has 88% coverage.

For all other regions we use commercial wind farm data from Ref. [34]. This dataset provides location, capacity and installation year of wind farms in many different countries. All wind park locations are labelled as "accurate" or "inaccurate". Accurate locations usually have coordinates verified inside or immediately adjacent to each wind farm, while inaccurate locations are at least positioned in the correct municipality (and sometimes better than this). Results obtained using these regions will not be as precise as for the regions with exact turbine locations since [1]: the park data covers an extended ground area and may e.g. contain multiple land types or varying protected area status; [2] some park locations marked as accurate appear to be centered on specific estates, where the park is located elsewhere on the same estate; and [3] not all wind parks for a region have their location marked as 'accurate'.

For an overview of selected regions, their wind deployment and quality of data, see Table 1. The accuracy column is marked *Exact location* for turbine level data. It is marked *Park* in countries where at least 80% of the parks in the data are labelled with "accurate" location, and at most 6% of the parks omit one of the properties: capacity (in MW), location (longitude/latitude coordinates), or installation year. If one of these properties is missing, the park is removed from the analysis, and the total installed wind power capacity is thus undercounted. In regions marked *Municipality,* up to 60% of parks lack accurate location (but are located in the correct municipality), and up to 10% of parks are excluded from the analysis due to missing capacity, coordinates, or installation year. In this case, it means that the accuracy of the data is too low for geographically detailed analysis of e.g. protected land. However, it is sufficiently accurate to calculate the aggregate deployment of wind power within a municipality.

In the case of Germany, where we have exact turbine location until 2015 and park level data from 2016 onwards, we have merged the two datasets. This merged data has municipality level accuracy. For analysis where higher accuracy is required, only the German data until 2015 is used.

Other geospatial datasets were obtained using the open-source GlobalEnergyGIS package, which rasterizes or rescales the datasets to a common resolution of 0.01°, or roughly 1 km at the equator [37]. Data on average annual wind speeds was extracted from the Global Wind Atlas [38] at 100 m altitude, which has been verified against other datasets [39]. Other datasets used include: data on protected land from the World Database of Protected Areas [40] and Natura 2000 [41]; data on administrative areas from the GADM project to delimit municipalities and counties [42]; data on land cover from the US Geological Survey [43]; and data on population densities for 2020 from staff at NCAR, who prepared data originally created by The Global Carbon Project [44–46].

2.3. Constraints on land availability

Constraints on land availability include *land cover* (cropland, forest, wetland etc.), *protection status* (natural reserves, national monuments etc.), and *population density.* To compare the installations of wind power on lands with different kinds of constraints on land availability, we report the average *installation density* per land area (lakes excluded) [kW/km^2]. As certain land cover categories are similar for the purpose of wind power installations, we aggregated Evergreen Broadleaf Forests, Deciduous Needleleaf Forests, Deciduous Broadleaf Forests, Mixed Forests, Woody Savannas and Closed Shrublands to the term "Forest". Open Shrublands, Grasslands and Savannas were merged into "Grasslands", and Cropland and Cropland/natural were merged into "Cropland".

To reduce the impact from sites which, regardless of their land cover, protection status, or population density, are unlikely to undergo wind power deployment, only those cells that have an average wind speed greater than 5 m/s are included in the analysis. We use data up to *park* accuracy. For wind parks, we use the land cover and population density in the grid cell that is stated in the dataset. Large parks may stretch over several cells, and thus other land covers. However, we do not believe that this assumption introduces a systematic bias.

We analyzed protected areas based on the protection classes provided by the WDPA. An alternative dataset of protected areas, Natura 2000, is only defined in Europe, and areas protected under Natura 2000 are also included in the WDPA. However, as some studies explicitly exclude Natura 2000 areas, we also performed an analysis for these classes separately. For an illustration of protected areas in Germany, see Fig. 1. We only use data with *exact locations* for the analysis, see Table 1. We include all sizes of turbines, as the mere occurrence of a wind turbine in a protected areas is what is of interest.

2.4. Deployment density

Deployment density is analyzed at the municipality level or county level (in the US), i.e. using administrative borders from GADM [42] level 3 for all countries. For this analysis we use all regions listed in Table 1, as we only need accuracy at municipality level. We calculate the *deployment density* in the municipality as the total MW installed wind power capacity divided by the total area in the municipality.

We choose this spatial aggregation level for several reasons. First, the effects on the landscape are mainly recognized locally; resistance against or support for wind power is typically generated locally; and, in many cases, the municipality has a mandate for making decisions related to wind farms. In Sweden, for instance, municipalities can veto the construction of new wind farms. Second, wind conditions are usually similar within a municipality, whereas, in most cases, they vary to a greater extent across a larger region. Third, since a municipality/county typically contains one or more cities or towns along with surrounding rural areas, we believe it is somewhat representative of the constraints on wind deployment exhibited in larger regions (state or country). Therefore, parameters quantified at this level (e.g., *deployment density*) should be consistent with the values obtained for more aggregated regions.

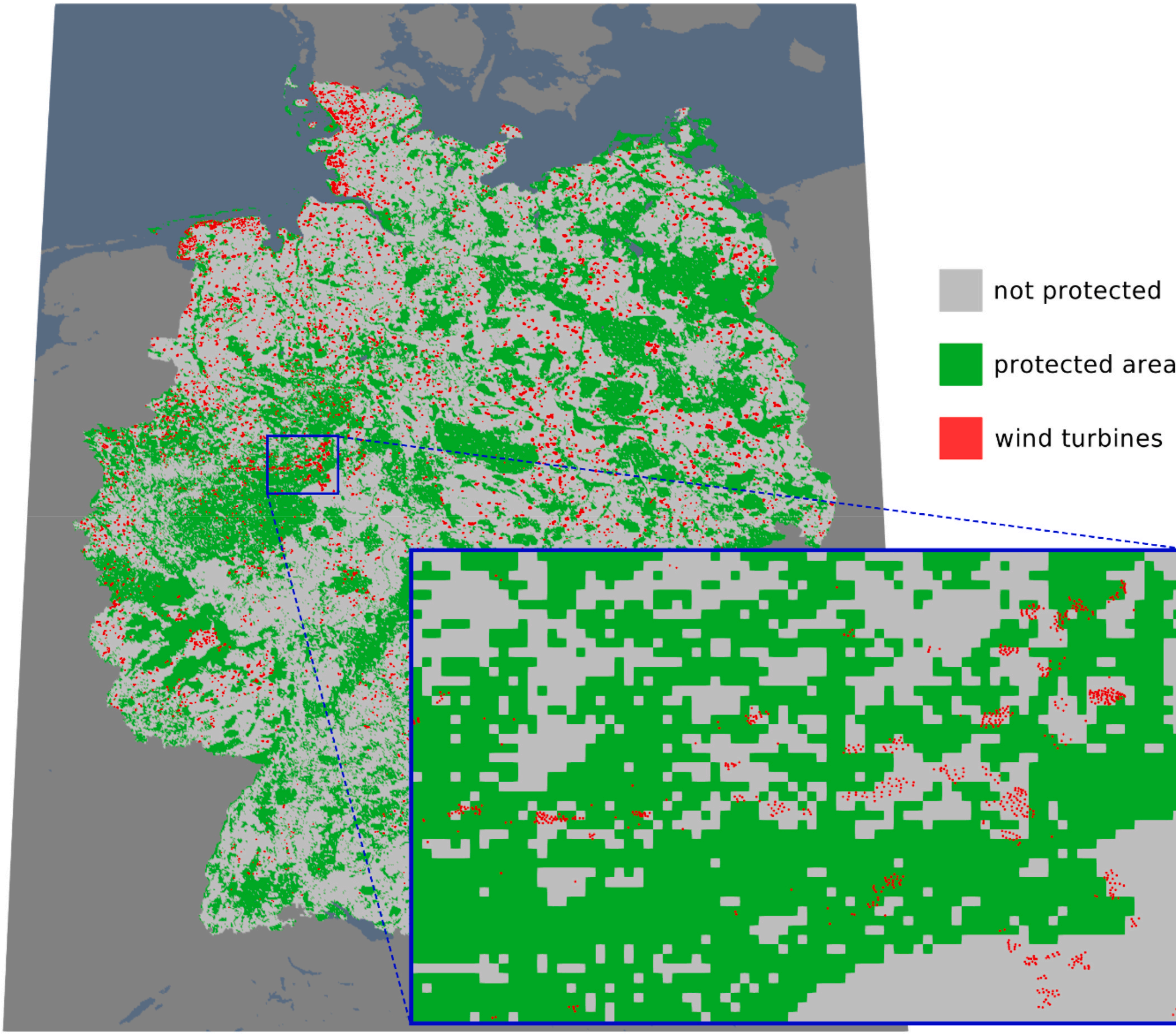

Fig. 1. Protected areas in Germany. The green color indicates areas that are protected under any of the eight definitions in the WDPA database. The red dots indicate individual installed wind turbines.

Finally, this aggregation level is generally sufficiently large not to be overly influenced by a single wind farm, yet small enough to generate a sufficient sample size for analysis.

2.5. Allocation with respect to wind speed

For *allocation with respect to wind speed*, we analyze the distribution of onshore wind power capacity as a function of wind speed at the grid cell level. We use data with *park* accuracy and higher. A large wind park may extend over more than one grid cell, however, we do not believe this introduces a systematic bias in the results, and thus use only the wind speed at the specified location of the park (often the center of the park).

In order to judge to what degree turbines have been installed at high wind speed locations, we compare the wind speed distribution at turbine locations with that of the wind speed distribution of the entire (onshore) region. Furthermore, we compare the average wind speed at turbine locations for turbines constructed up to 2014, to those after 2014. Thus, we can judge if there has been a shift to more, or less, windy sites over time.

3. Results

3.1. Constraints on land availability

We first determine whether there are easily identifiable types of land on which wind power consistently has *not* been installed at any significant level. Thereby, we can provide empirical evidence for the types of land that may be reasonable to exclude from wind resource estimates. In Fig. 2 and Supplementary Table 2, we show results for average installed capacity per km^2 for different land covers. It is clear that the highest density of wind turbines is found on croplands and grasslands. More importantly, wind power has been installed on all types of land cover, including those that are often excluded in models, such as urban land and wetlands (see Supplementary Table 2). However, more detailed temporal analysis shows that no wind turbines have been placed on wetlands since 2015, and also less at urban land and barren land, see Supplementary Fig. 1. Some regions almost lack a specific type of land cover; this explains most of the zero values in Fig. 2. An exception to this is forested land. In Oregon, 40% of the land (with an average wind speed

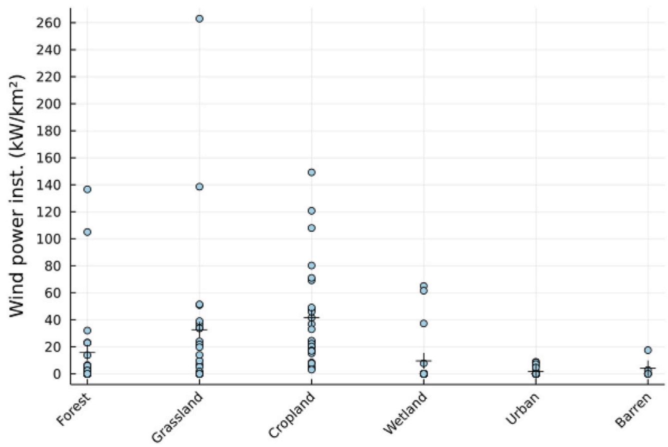

Fig. 2. Wind installations on different land cover types for the 25 analyzed regions. The black crosses represent the average for the land type, while the blue circles indicate the extent of wind installation in a specific region. Regions in which the land cover type does not exceed 0.1% of the total land cover are excluded.

above 5 m/s) is covered by forest, but no wind turbines have been installed there (see Supplementary Table 1). In contrast, Sweden and Germany, both of which have a large share of forest, display a density of wind turbines in forests that is similar to that on croplands in many US states .

The same land area may have several different protection statuses. Here, we analyze the classification made by WDPA and the EU classification Natura 2000 areas using the 14 regions classified with *Exact location* accuracy, see Fig. 3. Most of the protection statuses display some wind power deployment (see Supplementary Table 2). These installations may to some extent be explained by limitations in the resolution of the data (see the *Discussion* section). It is also evident that, compared to Denmark, Germany, and Sweden, a smaller share of the land in the US is protected, and areas that are protected are used for wind power to a lesser extent.

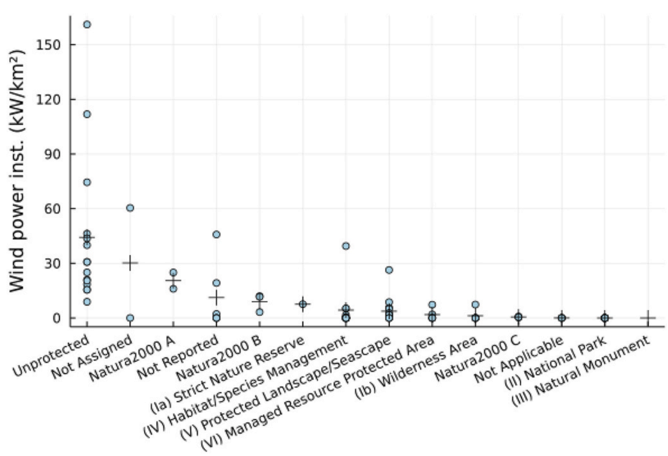

Fig. 3. Wind deployment on various categories of protected areas in the WDPA and Natura 2000 classifications for the 14 analyzed regions. The black crosses indicate averages for all regions, and the blue circles represent capacities in specific regions. As a comparison, unprotected areas have an average wind power deployment of 45 kW/km^2. If a specific protection status constitutes less than 0.1% of the total land in the region, the data-point is excluded. The Natura2000 areas only exist in the EU, i.e., for Sweden, Germany and Denmark in our dataset.

As may be deduced from Fig. 2, wind power has been deployed in some areas that are classified as urban land. However, urban land areas are in some contexts defined in terms of population density[1] rather than land cover, which affects, for instance, the classification of industrial areas. As a consequence, some studies [5,27] have applied population density as an additional constraint on wind deployment. In Fig. 4, the average installation density [kW/km^2] is plotted as a function of population density using the 25 regions classified as having at least *Park* location accuracy. It appears that wind power has been installed on land areas with almost all levels of population density, even in areas with a density as high as between 1000 and 5000 people per km^2. Only land with population density greater than 5000 persons/km^2, which corresponds to the population density of metropolitan city centers, has not been used for wind power. However, only a few regions have higher installation density on heavily populated land, so there is evidence of reduced wind power deployment as population density increases. Simultaneously, the installation density is lower on very sparsely populated land, possibly an effect of less nearby transmission infrastructure, and energy demand.

3.2. Deployment density

Fig. 5 shows the *deployment density*, i.e. the average wind deployment per km^2 in each municipality or county in the 28 regions with at least municipality accuracy of the data. Only municipalities/counties with at least 10 MW of installed wind power capacity are included in the analysis, which means that 1243 of 3655 municipalities/counties are included. Similar figures of *deployment density* for each individual region may be found in the Supplementary Figs. 2–29.

Note that some municipalities have high levels of wind power relative to their surface area. The observed distribution of *deployment density* for municipalities extends up to around 0.7 MW/km^2, with rare outliers up to 1.5 MW/km^2. A *deployment density* of 1.5 MW/km^2, is effectively equivalent to wind farms occupying between 10% and 20% of the surface area of the municipality. While municipalities with high wind power deployment do exist, most municipalities currently display low *deployment density*, with a median of 0.077 MW/km^2 and a mean of 0.126 MW/km^2 of all land.

It is plausible that regions with a higher overall deployment density

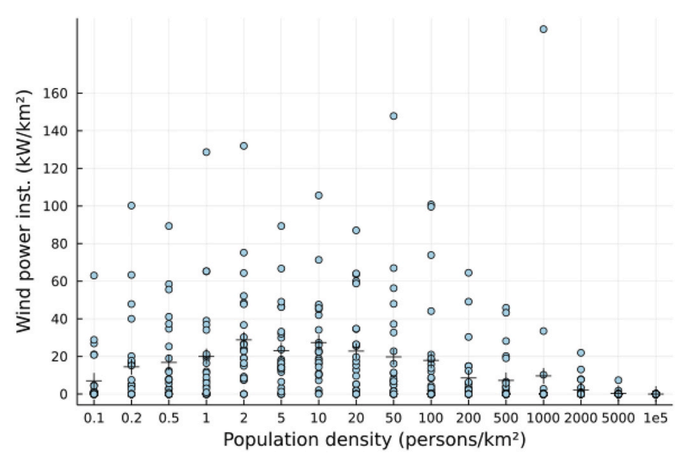

Fig. 4. Wind deployment in relation to population density for the 25 analyzed regions. The black crosses indicate averages across all regions, and the blue circles show capacities in specific regions.

[1] The US Census Bureau defines an urban area as "core census block groups or blocks that have a population density of at least 1000 people per square mile (386 per square kilometer) and surrounding census blocks that have an overall density of at least 500 people per square mile (193 per square kilometer)".

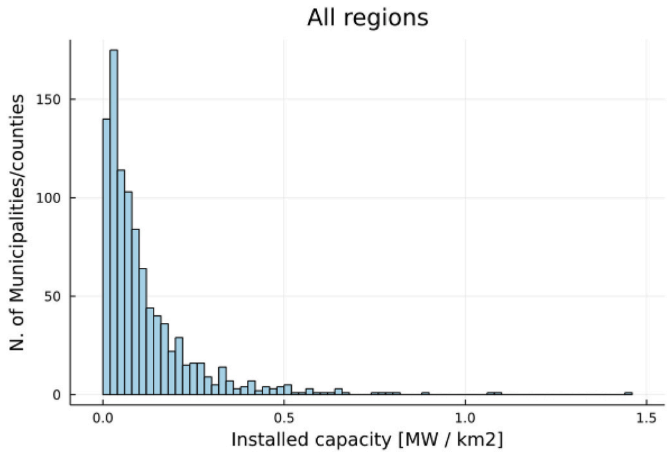

Fig. 5. The deployment density of wind power installations per municipality. Only counties/municipalities with more than 10 MW installed capacity are shown.

also tend to have municipalities with high deployment density. Fig. 6 shows the relation between the overall deployment density in the region and the deployment density in the 5 most densely deployed municipalities. As can be seen, the relation appears rather weak and is not unequivocal. We observe that a municipality level deployment density over 0.5 MW/km^2 is uncommon, regardless of the overall deployment in the region. The two main exceptions are Germany and Portugal, where several municipalities reach above 0.5 MW/km^2. We also explore whether there is a relation between deployment density and population density in the municipality. As shown in Figure 30 in Supplementary material, this does not seem to be the case.

3.3. Allocation with respect to wind speed

Next we investigate how wind power has been allocated with respect to wind speed in the different regions. Fig. 7 shows an example of the wind speed distribution of all the land in the region (blue) and of the land with wind power installations (red) for Denmark and Colorado. In Denmark, there is only a small shift towards windier sites in relation to the wind endowment, and it is evident that wind power has generally been deployed at sites with all wind speeds. In contrast, Colorado displays a wider distribution of wind speeds, with more than 10% of the land with a wind speed of less than 5 m/s, but the wind turbines are

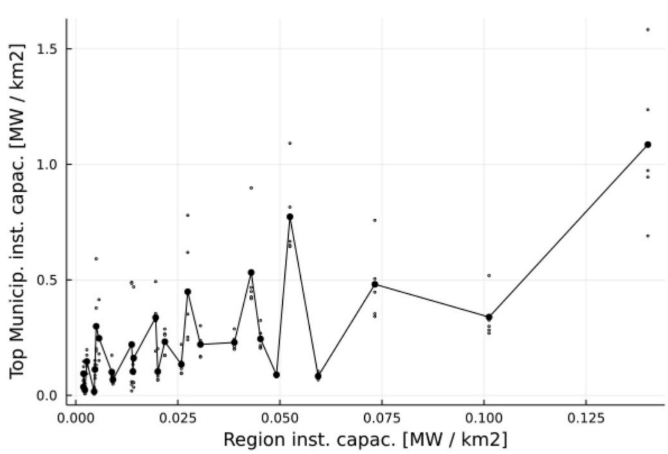

Fig. 6. The deployment densities in the five municipalities/counties with the highest deployment density as a function of the average deployment density in the overall region. The line and heavier dots indicate the mean deployment density in each overall region.

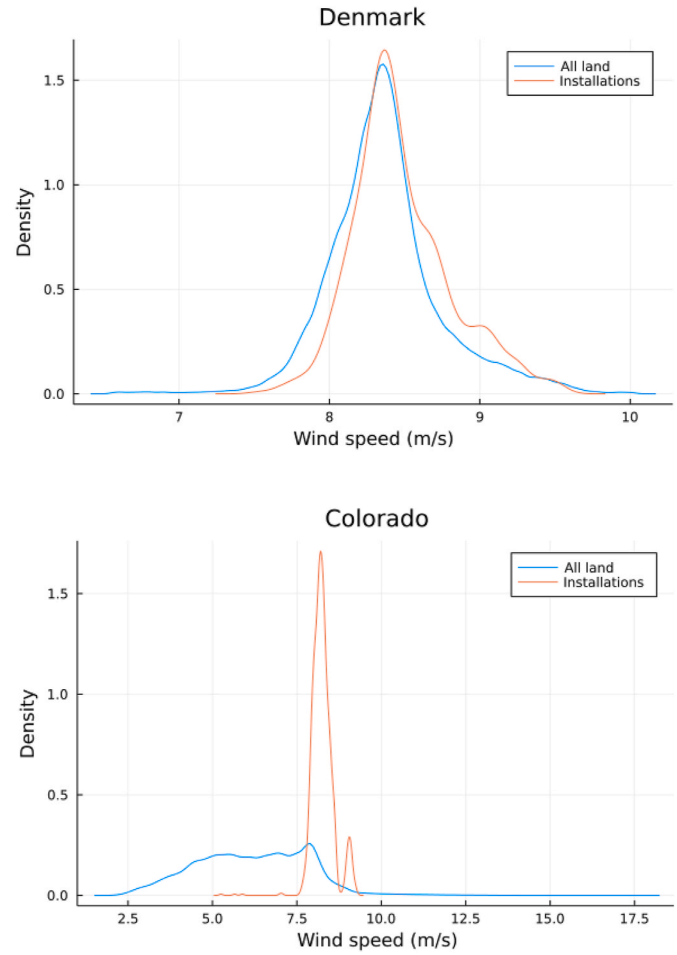

Fig. 7. a and b. The distribution of wind speed in the entire region and the distribution of wind speed in cells where wind power turbines are located in Denmark and Colorado.

clearly concentrated at sites with the highest wind speeds. However, overall the capacity allocation is quite similar for the two cases, despite different endowment patterns. When analyzing all regions (see Supplementary Figures 31-55), substantial differences in the *allocation with respect to wind speed* between regions can be observed. For instance, Quebec and South Australia have similar wind speed distribution, but wind power in South Australia is sited at significantly more windy sites. Yet, a common feature of all 25 regions is that there appears to exist a lower limit, such that sites with average wind speeds below 6 m/s are used only to a very limited extent.

Fig. 8 shows the mean wind speeds of all land (weighted by area) and the mean wind speed for sites with existing wind turbines in each of the 25 regions. As expected, the mean wind speed at sites with installed wind capacity are in all cases higher than the mean wind speed of the entire region. The largest differences between the mean wind speed of the entire region and the wind speed of sites with installed wind power can be found in regions with the lowest average wind speeds.

In Fig. 9 we plot the average wind speed for wind turbines installed before and after 2014 in each region. The overall conclusion is that turbines are mostly placed at sites with similar wind conditions before and after 2014, but there is a weak tendency for wind turbines to be installed at slightly less windy sites after 2014 compared to before 2014. However, for some regions, the opposite is true.

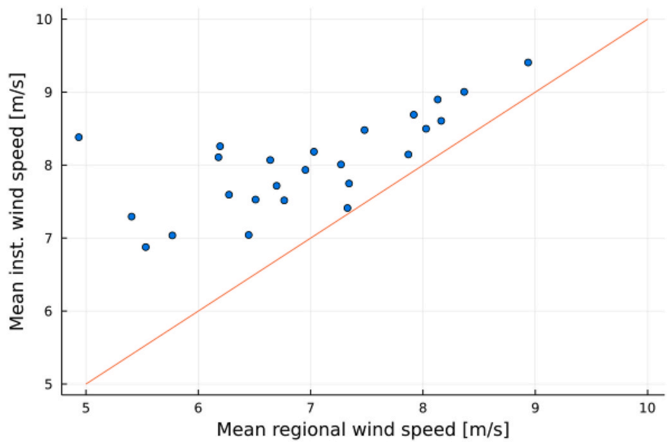

Fig. 8. Mean wind speeds (weighted by area) for a region vs mean wind speeds for sites with installed wind turbines in each region.

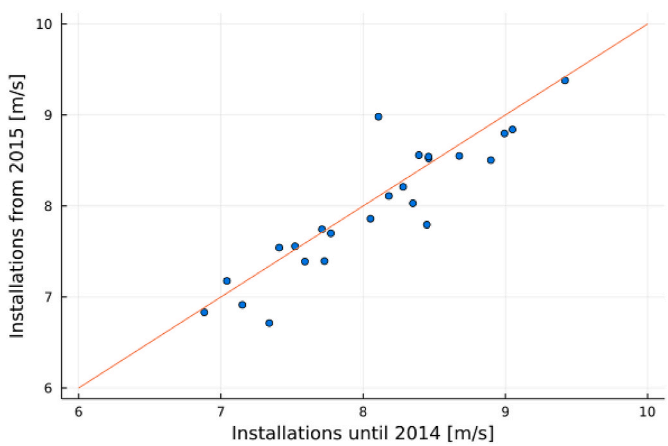

Fig. 9. Average wind speed of sites with wind turbines installed up to 2014 and after 2014.

4. Discussion

4.1. Data limitations

We have used between 14 and 28 regions for our analysis, which represents most countries and states that have installed a substantial amount of wind power to date. There are thus reasons to believe that general patterns found in this sample can be generalized to countries and regions that will install wind turbines in the near future. For some regions, we have excluded turbines due to incomplete data, up to 6% for data with *Park* accuracy, and up to 10% for data with *Municipality* accuracy, thus underestimating the total installed capacity in these regions. However, we do not believe there is a systematic bias for the turbines that were excluded with respect to land type, protected status, or population density. Thus, we believe that at least the relative distribution of turbines for these properties is correct, while at the same time the actual total deployment might be slightly higher in reality. Also, with regards to deployment density within municipalities, we may be undercounting the installed capacity by up to 10% for some regions. However, most regions have significantly fewer missing turbines than this, and therefore we believe our data are sufficiently accurate for the analysis.

For the analysis of protected areas, while we have exact coordinates for the locations of wind turbines, our other datasets have a finite resolution, which leads to potential misrepresentations in our results. Our working resolution of 0.01° (roughly 1 km) means that we may occasionally make classification errors at this scale, e.g., if a wind turbine is close to the boundary of a protected area it may be labelled as being within a protected area in our analysis. However, it is clear that multiple regions have turbines placed in the interior of large protected areas, though this can not necessarily be generalized to all kinds of protection statuses in every region.

Similarly, for analysis of land cover and population density, we only have the approximate location of wind parks in many regions. This may also lead to classification errors, if for instance the location of a park is near the fringe of a specific land cover or population density. However, we do not have reasons to believe that this imposes a systematic bias in favor or against a specific land cover or population density.

4.2. Comparison with assumptions made in energy system models

Our findings show that onshore wind power has been placed on all land covers, e.g., on grasslands, forestry areas, and wetlands. Wind turbines have also been placed on some types of protected areas. These results regarding historical deployment are contrary to assumptions that have been made in many energy systems models, in which certain land types, such as wetlands and nature reserves, have been assumed to be unavailable for wind power deployment [18,27,37]. The implication here is that in some cases the practice of excluding land types in energy system models is not in line with historical patterns of wind power deployment and may therefore underestimate the onshore wind power potential. However, as the land types excluded (e.g. wetlands) typically constitute a rather limited share of the total land area, the effect on the overall wind potential is likely small.

Regarding the special cases of urban land and densely populated areas, we find that land classified as urban has indeed been exploited for wind power (see Fig. 2). In terms of population density, we find that wind power has been deployed in areas with population densities as high as 2000 persons/km^2, even though heavily populated areas tend to have less wind power than less-densely populated areas (see Fig. 4). These results are consistent with the results presented by Lau et al. [47], who investigate how wind power deployment in Sweden and Germany depends on population density. The results are, however, discrepant with assumptions made in some energy systems models. For example, MacDonald et al. [27] apply a constraint whereby the population density reduces the exploitable area by 5000 m^2/person, with the consequence that areas with a population density above 200 persons/km^2 are completely excluded for wind power deployment. Similarly, Reichenberg et al. [48] exclude areas with a population density greater than 150 persons/km^2. Thus, the empirical data suggests that the cut-off for wind power deployment with respect to population density should be higher than that employed in some models.

We find that the *deployment density* in municipalities seldom exceeds 0.5 MW/km^2. However, the fact that we measure *deployment density* as part of *total* land means that the relevant comparison to energy system models is the combined result of removing land types, the capacity densities of wind parks and the share on the remaining land that are assumed to be suitable for wind deployment. In the literature, Bogdanov and Breyer [26] do not remove any land types, instead assuming that the maximum deployment in a region is 0.3 MW/km^2. Reichenberg et al. [5] remove on average 25% of the land based on land types and population density, and then assume that 4% of the remaining land might be used for wind parks (with a capacity density of 5 MW/km^2), which gives an deployment density of 0.15 MW/km^2. MacDonald et al. [27], on the other hand assume a deployment density between 0.5 MW/km^2 and 2.5 MW/km^2 in the US, which seem optimistic in the light of historical deployment.

Unlike explicit or implicit assumptions in many models, wind power is not placed exclusively at the windiest sites, only to move down the windiness ladder when these sites are already filled up. In part, this is because some windy sites suitable for wind deployment may lack access to grid or other infrastructure. Still, this is not the only mechanism at play, as sites with medium wind conditions are used even if there are more windy sites available. Model assumptions of cost-effectiveness, that thereby mainly allocate wind power to the windiest sites [28,48], do not mimic the historical pattern for *allocation with respect to wind speed*. Other model studies, on the other hand, assume that power is distributed over all available land [17,18], whereas we find that it is very uncommon to find wind turbines at sites that have wind speeds lower than 6 m/s.

4.3. Further research

In this analysis we have looked at all regions simultaneously, with the aim of understanding general patterns. However, the institutional setting varies between regions, and there may very well be countries or states where rules, practices, and regulations consistently exclude certain types of land. *Deployment densities* also vary significantly between regions. If the goal is to reflect the socio-political reality in each region, it may be problematic to assume one specific value for a large geographic area, especially if institutional settings differ. It may be possible to explain the difference in deployment patterns between regions by analyzing aspects such as institutional frameworks, drivers for wind deployment, geography, and socio-political conditions.

It should also be noted that it is uncertain whether the patterns of deployment of wind power in the future will resemble those in the past. We have in this paper focused on larger turbines, and also done some limited analyses of time trends, and have not detected major shifts over time. Still, the technology as well as the socio-political reality change. It is unclear whether the most wind power intensive municipalities have yet reached their socio-political upper limit for onshore wind exploitation, or if municipal deployment densities may exceed 1 MW/km^{2}in the future.

Our investigation of land types where wind power has been allocated does not include an analysis of terrain slope. This is a factor that is considered for excluding land in some energy system models [27,49]. However, in order to investigate the slope, a considerably higher resolution of spatial data is necessary, which is the reason why such an analysis is not part of this paper, but could be performed with more detailed datasets.

As expected, wind power tends to be deployed at windier sites. However, there is also large variability, and clearly some less-windy places are exploited despite windier sites remaining untouched. There are several possible reasons for this. First, the data used here may not mirror actual wind speeds because with more reliable local measurements, companies may choose windier sites than what our global data indicates. Second, there may be various constraints on deploying additional wind power at windy sites, e.g., regulations, lack of infrastructure, public resistance etc. Third, access to a well-functioning socio-technical system may affect the spatial diffusion of wind power. We do find a slight shift towards installations at sites with lower wind speeds after 2014, as compared to earlier installations (see Fig. 9). It is possible that some suitable windy sites have been depleted for wind deployment. Also, wind power technology has developed to capture lower wind speeds, and costs have decreased, during this period. Consequently, less windy sites have become cost-competitive, which may be part of the reason why the average wind speed for installed capacity has decreased slightly over time for some regions. Still, windier sites in general remain more profitable than less windy ones. Further and more detailed analysis is required to understand if the trend towards less windy sites is consistent and likely to remain.

The potential for wind power, which in models is expressed using *deployment density* and rules for excluding land, has implications for not only the amount of wind capacity that may be installed in a larger region but also the cost of wind power. The *allocation with respect to wind speed*, on the other hand, affects only the cost-efficiency of wind power in a model, since an allocation method that assigns wind installations also to less-windy sites reduces the cost-efficiency of wind power compared to other power sources. Thus, the analysis performed in this study has implications for both the upper limit on wind power deployment and the cost-efficiency of wind power in a particular model. However, the full implications of these assumptions for future scenarios need further exploration.

5. Conclusions

We have analyzed new empirical data related to historical wind power deployment in 14–28 regions across the world. While energy system studies have made assumptions regarding where wind power may be deployed in the future, it has not previously been possible to compare those assumptions to empirical data. In this first analysis, we conclude that:

- Wind power has been deployed on most land types, including most types of protected areas and densely populated areas (far above the limit of 150–200 persons/km^2 assumed in some models). In contrast, many model studies exclude land types such as wetlands, natural reserves and urban land.
- The average deployment density in municipalities seldom exceeds 0.5 MW/km^2. In contrast, some models apply more generous maximum *deployment densities*, even though the models typically apply restrictions to regions that are considerably larger than municipalities.
- Wind power has rarely been deployed at sites with average wind speed below 6 m/s. However, we do not see any evidence for a strategy that exploits sites with lower wind speeds only when windier sites are already used up. In contrast, many models use the best-sites-first rationale when allocating wind capacity.

Contributions

Fredrik Hedenus: Conceptualization; Methodology; Formal analysis; Project administration; Funding acquisition; Writing – original draft, Niklas Jakobsson: Software; Visualization; Formal analysis; Writing – review & editing, Lina Reichenberg: Conceptualization; Methodology; Investigation; Writing – original draft, Niclas Mattsson: Software; Formal analysis; Data curation; 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

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112813.

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