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Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide

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ABSTRACT

Differing estimates have emerged about how much land or water area is used by existing wind farms and how much power can be obtained from that area. Whereas, no single unique method exists to define wind farm spacing area, the spacing area (thus installed and output power densities) of a wind farm can be determined in a way to meet specific logical criteria, This study proposes a new, intuitive, data based, automatized method of estimating spacing areas occupied by existing onshore and offshore wind farms worldwide. The method eliminates the erroneous counting of space outside of wind farm boundaries, space between clusters of turbines, and overlapping space that results when assuming a large fixed area around each turbine. At least one of three types of extra space has incorrectly been included in all calculations of wind farm areas to date. Unlike most previous methods, this method also ensures that the addition of a wind turbine to a farm increases the overall required spacing area of the farm. The study then uses data from over 1600 operating wind turbines in 16 onshore and 7 offshore wind farms in 13 countries across 5 continents during the period 2016–2018 to quantify installed and output power densities of these farms. Finally, it compares results with estimates from other studies. Results indicate that the mean (range) installed and output power densities of onshore wind farms in Europe are 19.8 (6.2–46.9) MW/km^2 and 6.64 (2.3–8.2) W/m^2, respectively; of onshore wind farms outside of Europe are similarly 20.5 (16.5–48) MW/km^2 and 6.84 (4.81–11.2) W/m^2, respectively; and of offshore wind farms in Europe are 7.2 (3.3–20.2) MW/km^2 and 2.94 (1.15–6.32) W/m^2, respectively. The mean capacity factors in each case are thus 33.5%, 33.4%, and 40.8%, respectively. These results indicate substantially higher installed and output power densities than previously reported, based simply on different definitions of land area, with no impact on capacity factor. Thus, existing wind turbines may extract more wind power over less land or water than previously thought.

Introduction

Wind farms are being installed worldwide at an ever-increasing rate. In 2018 for example, 48% of all new European Union (EU) nameplate capacity for electricity generation was from wind (Wind Europe, 2019), and in 2018 wind satisfied 15% of the EU's electricity demand (Wind Europe, 2020). However, projections of future wind growth worldwide depend on several factors. Factors that may limit growth include limited remaining high-wind-speed locations near load centers, transmission constraints, competition between wind farms and other land and water uses, and social opposition (Wizelius, 2007; Enevoldsen & Sovacool, 2016; Nadaï & van der Horst, 2010). On the other hand, wind turbine nameplate capacities, hub heights, rotor diameters, and outputs have been increasing over time, increasing the productivity of wind farms (Wiser et al., 2020).

The power output produced by a wind farm spread over a given area of land or water depends not only on characteristics of the wind turbines and of the wind resource, but also on array losses that arise due to competition among wind turbines for available kinetic energy (Masters, 2001; Jacobson & Archer, 2012; Ritter et al., 2017; Jacobson et al., 2014; Archer et al., 2019; Nygaard et al., 2020; Porté-Agel et al., 2020; Pan et al., 2018). However, as found in Jacobson and Archer (2012), spreading the same number of wind turbines (and total nameplate capacity) over more wind farms that are separated by distance increases substantially the power output among all wind turbines in all farms. The reason is simply that, when wind farms are separated by distance, each experience less competition for available kinetic energy because more turbines are on the edge of the farm and more turbines have fewer upstream turbines extracting upstream energy. In fact, Jacobson et al. (2018) found that spreading 13 TW (nameplate capacity) of wind in farms among 139 countries to provide 37.1% of the world's end-use all-purpose power resulted in power output from the turbines that was only ~6.7% lower when competition for kinetic energy was accounted for versus when it was not. In sum, whereas competition

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among turbines occurs and causes losses, total losses are reduced when wind farms are separated by distance.

Because most countries of the world are or will be installing significant quantities of onshore and offshore wind, over limited land areas, many wind planners worldwide would like to know how much nameplate capacity of wind can be installed over a given land area and the resulting output. Central to this issue, of course, is what land or water area (referred to here as spacing area) is considered part of the farm. The purpose of this paper is to propose an automatic method of determining the spacing area essential to a wind farm, and consequently, the installed power density (nameplate power capacity per unit land or water area) and the output power density (wind farm power output per unit land or water area). For this study, we use real wind farm data primarily from Europe, but also from the rest of the world, first to quantify the spacing areas of existing wind farms then to quantify a mean and range of wind farm installed and output power densities.

Aside from reducing land requirements thus land costs, an advantage of a higher installed power density is a reduction in the cost of transmission between turbines in a farm (Hou et al., 2015; Hou et al., 2017). A disadvantage is increased wake-induced fatigue loads for the turbines located downstream, which may lead to reduced lifetimes and/or premature damage to components of the wind turbine (Manwell et al., 2009). An additional impact of high-density installations is the lower annual energy production per turbine due to increased competition among wind turbines for available kinetic energy (Masters, 2001; Jacobson & Archer, 2012; Ritter et al., 2017; Jacobson et al., 2014; Archer et al., 2019; Nygaard et al., 2020; Porté-Agel et al., 2020; Pan et al., 2018).

Systematic quantification of the installed power density is important because current estimates of it over land vary by a factor of 9.1, from 1.5 to 13.6 MW/km^2, with a mean of 7.2 MW/km^2 (Fig. 1), due to different definitions of the land area that constitutes a wind farm. For 8.33 TW of nameplate capacity of onshore wind alone in 2050 to provide 2.77 TW of end-use power (satisfying 23.5% of all demand) among 139 countries (Jacobson et al., 2017), that could mean a difference between wind occupying 0.61% versus 5.55% of the 139-country land area.

Similarly, due to different estimates of land requirements, the estimates of output power densities for large-scale onshore wind farms have ranged from 1 W/m^2 (Miller et al., 2015) to 1.2 W/m^2 (Bryce, 2010) to 2 W/m^2 (MacKay, 2008).

For offshore wind, the range in installed power density is 3 to 12 MW/km^2, with a mean of 7.36 MW/km^2 (Fig. 2).

Installed and output power densities of most studies referenced in Figs. 1 and 2 were based on theoretical calculations. In Enevoldsen and Valentine (2016) and in the present study, results are based on wind farm data. In Miller and Keith (2018), some operational wind farm data are also analyzed. Almost all previous studies of installed power density have assumed that each turbine occupies a specific rectangular, circular, or polygon ground surface area determined as a function of rotor diameter or mean distance between turbines (Miller & Keith, 2018; Jacobson & Masters, 2001; Meyers & Meneveau, 2012) or as a function of distance from the ground to the highest extent of the turbine blade (Christie & Bradley, 2012).

Whereas, assuming that each turbine occupies a specific plot of land or water is useful for designing a wind farm so that wind turbines are sufficiently separated to reduce array losses, such a method is too simplistic for determining how much spacing area is actually occupied by the farm once it is built, thus inaccurate for determining the final installed and output power densities of a farm. The assumption falls apart particularly when the wind farm is linear, contains rows of turbines separated by great distance, contains multiple clusters of turbines, or otherwise exhibits a complex geometry. It also overestimates spacing areas, as discussed shortly. As such, we believe a new method of calculating spacing areas for existing farms is needed.

Aside from the new method, a novelty of the study is that it is applied with data to calculate the installed and output power densities of existing (old and new) wind farms over five continents. Previous studies have focused on one continent. Results here are also compared with those from previous studies.

Materials and methods

Defining wind farm spacing areas

Although there is not one unique way to define wind farm spacing area, the spacing area (thus installed and output power density) of a wind farm can be determined in a way to meet specified logical criteria, Here, we propose a new, intuitive, data-based, automatized method of estimating the spacing areas required for, thus installed power densities of, onshore and offshore wind farms worldwide. The spacing area of a wind

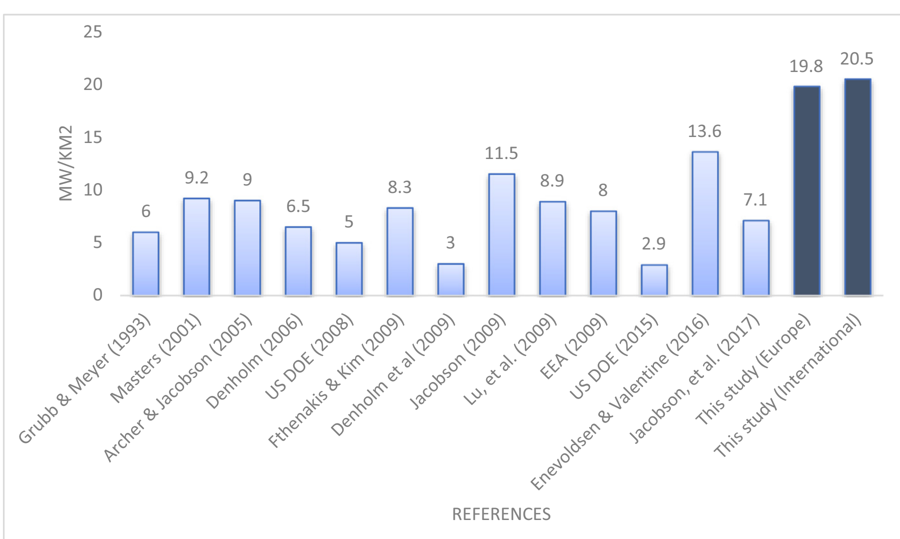

Fig. 1. Estimated installed power density of onshore wind turbines from previous studies[1] and the present study. The mean (range) of the previous estimates is 7.2 (1.5-13.6) MW/km^2, which compares with the mean from operational wind farms presented in this study (19.8 MW/km^2 for European wind farms, and 20.5 MW/km^2 for wind farms outside of Europe) (Grubb & Meyer, 1993; Masters, 2001; Archer & Jacobson, 2005; Denholm, 2006; US DOE, 2008; Fthenakis & Kim, 2009: NREL, 2009; Jacobson, 2009; Lu, et al., 2009; EEA, 2009; US DOE, 2015; Enevoldsen & Valentine, 2016; Jacobson, et al., 2017).

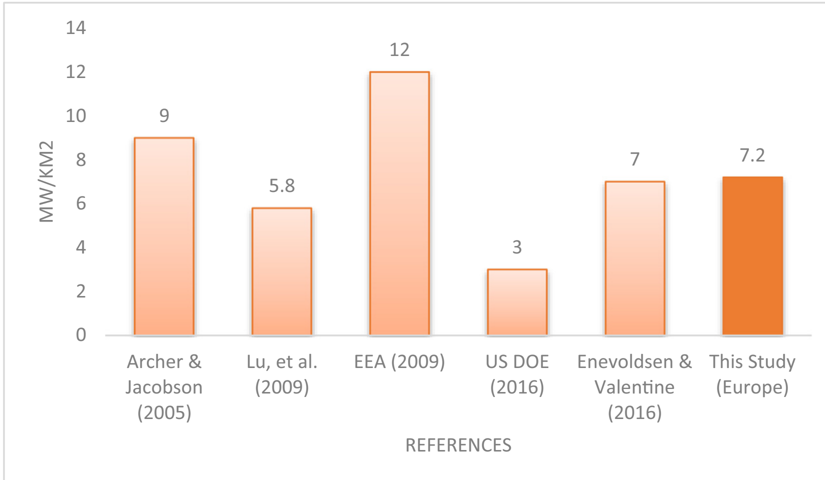

Fig. 2. Estimated installed power density of offshore wind turbines from previous studies, and the present study. The studies indicate a range of 3–12 MW/km^2 and a mean of 7.36 MW/km^2. (Archer & Jacobson, 2005; Lu et al., 2009; EEA, 2009; Energy.gov, 2016; Enevoldsen & Valentine, 2016) .

farm differs from its footprint, which is the area of a turbine tower and base touching the top of the ground (either land or water). The spacing area, which encompasses the footprint, is the total area between and immediately around a wind turbine (Jacobson et al., 2017). However, it also includes the area to install and dismantle the wind turbine. The spacing area between wind turbines can be used for multiple purposes (e.g. agriculture, range land, solar panel installation, open space). The installed power density of a wind farm is inversely proportional to the spacing area of the farm. Greater installed power densities imply greater potential installations of wind over smaller land or ocean areas.

The method of calculating wind farm spacing area developed here eliminates the erroneous counting of space outside of wind farm boundaries, unrelated space between clusters of turbines, and overlapping space that results when assuming a large fixed area around each turbine. At least one of all three types of extra space has been included in all calculations of wind farm spacing areas to date. The new method also ensures that the addition of a wind turbine to a farm increases the spacing area required. The spacing area we define is not optimized to maximize power output of the wind farm by minimizing interference among wind turbines. In fact, our methodology is based on the spacing areas of wind farms that have already been built. The methodology is thus not designed to provide the ideal distance between turbines for the planning of new farms. Instead, with the spacing areas provided here, it is possible to estimate how much land might be taken up with future wind development assuming that future installed power densities are the same as those of existing farms. Further, unlike other methods, the method developed here ensures that erroneous land or water areas are not included in the spacing area calculation.

The key challenge of this study is to develop an automatic, objective method of calculating wind farm spacing area that makes physical sense and is repeatable with a transparent methodology. The new method is described here, illustrated in Figs. 3 and 4, and applied in Figs. 6, 7 and 8.

In general, the method involves defining three areas. The areas assume that a wind farm consists of one or more clusters of individual wind turbines. The first area is simply a circular area around each turbine (the red circles in Figs. 3 and 4), where the radius of each circle is the maximum (tip) height of the turbine (the hub height plus the radius of the rotor diameter). The tip height is chosen, since it is the maximum physical horizontal distance a turbine can extend if it falls. This distance also ensures that, if a wind turbine is at the edge of a farm, no space beyond this distance can be counted as part of the wind farm spacing. Thus, the edge of a farm will extend no more than one tip height from the turbine tower. This differs from all other studies, which assign spacing to wind turbines 3–6 rotor diameters or more from the tower, thus include as spacing substantial area beyond the edge of the wind farm.

The area in between clusters is not included as spacing area, because the land is often used for agricultural purposes, industrial purposes (e.g., forest industry), or for other energy technologies (e.g., solar PV).

Some may suggest that open space between clusters of turbines in a wind farm should also be counted because it is space that paid for by the developer. We disagree because (1) developers often lease land rather than purchase it and (2) we believe the area should not be counted

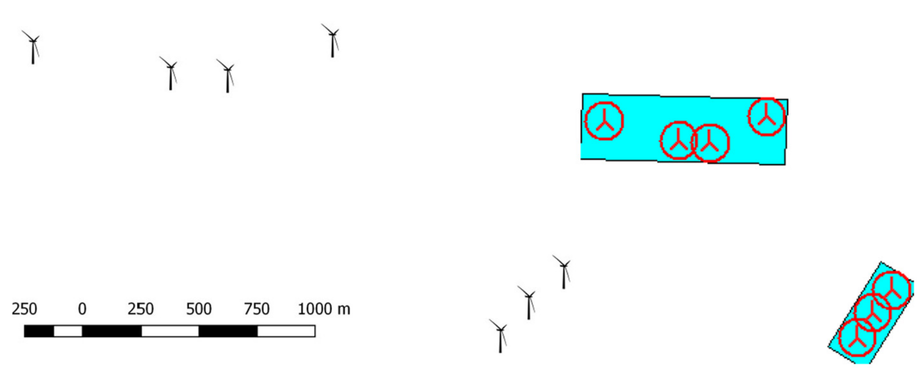

Fig. 3. Example wind farm layout #1. It consists of seven wind turbines, all with a hub height of 80 m and a rotor diameter of 93 m, located in semi-complex terrain. The red circles represent the tip height of each wind turbine (hub height + rotor diameter/2). The second area is the spacing area of all turbines in a cluster. This is an area traced around the edges of the circles around each turbine on the outside of the cluster (blue areas in this figure and Fig. 4), and incorporated in Figs. 7, 8, and 9. This area includes the areas of the circles within the cluster. A cluster is defined as separated from another cluster when the distance from a turbine tower to a neighboring turbine exceeds three times the tip height (hub height + rotor radius) of the turbine. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

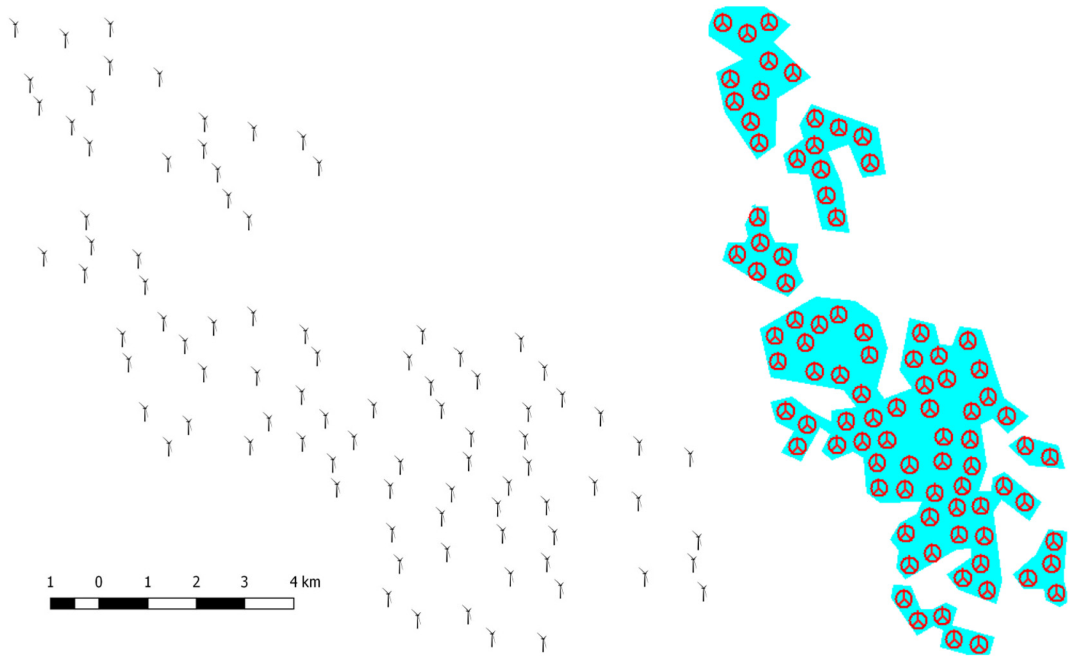

Fig. 4. Example wind farm layout #2. The farm consists of 140 wind turbines, each with a hub height of 65 m and a rotor diameter of 93 m, located in flat terrain.

until it is actually developed since it remains open space until then. A developer may purchase additional land for future wind turbine additions or as an investment to sell later. Regulations based on visual or noise impacts may also limit the number of turbines on a property.

Roads exist only in onshore wind farms so have no impact on offshore wind turbine spacing areas. For onshore wind farms, the areas of roads and other infrastructure within each cluster are automatically accounted for, since the spacing area determined here includes all area within the boundaries of a cluster. If road data outside of clusters are available, we would consider such data (e.g., Fig. 4). However, in such cases, we believe only paved roads should be considered as part of the spacing area of a wind farm, because if roads are unpaved, then the roads often return to their natural habitat, even during the life of the turbine. Unpaved roads in arid regions in particular, blend in with the natural habitat.

The third area is the final, overall spacing area of the wind farm. It is simply the sum of the spacing areas of all clusters within the farm. Since the overall spacing areas we calculate are determined from existing wind farms, they automatically take into account topographical variations that arise in those farms.

The computing of the wind farm spacing area was conducted using the open-source software QGIS (https://www.qgis.org/en/site/) by following five simple steps: 1) determining wind turbine characteristics and location; 2) applying a buffer zone equal to the tip height; 3) connecting polygons between buffer boundaries if they are within the predetermined distance quantified in the above paragraphs, which describe a distance threshold of three times the tip height (for wind farms with homogenous wind turbine configurations); 4) creating new polygon clusters for wind turbines outside the range; and 5) manually checking for transformer stations, etc., which is part of the wind farm's land use. This methodology does not equal a suggestion for deploying wind turbines with a tip height distance in between. The tip height definition is merely a sound distance requirement. The suggestion spacing density can be derived from the conclusion of this paper.

Fig. 3 shows an example wind farm consisting of two clusters of wind turbines separated from each other by a protected forest. The two clusters are treated separately, and their areas are added together to estimate the total wind farm spacing area. The area of each cluster in this case is determined by placing a rectangle around the outermost edges of the red circles around individual wind turbines in the cluster.

For larger wind farms than in Fig. 3, such as in Fig. 4, the same approach is used, but geometric areas, rather than rectangles, are drawn around each cluster. The geometric area is a tip height away from turbines on the outer edge of the cluster. In this specific case, roads, transformer buildings, etc. were included as part of the spacing area of the wind farm, which is why the shape of the farm has a certain ruggedness. The area of the roads, which were constructed to support the access to and from the wind farm, and of buildings, was small.

We draw specific areas around clusters of turbines rather than simply multiplying the number of wind turbines by an area assigned to each turbine. In addition, we do not double count land where future projects might overlap, as has been done in some previous studies. The approach of assigning pre-defined wind turbine areas rarely reflects reality, as wind project developers usually alter layouts due to wake effects (Wizelius, 2007) and socio-political reasons (Enevoldsen & Sovacool, 2016). The advantage of the new method introduced in this study is that it eliminates inaccurate assignments of spacing areas beyond the outside edges of clusters, it accounts for the fact that many wind farms contain clusters of turbines separated by distance, and it accounts for actual distances between wind turbines within clusters. Furthermore, this study draws on exact coordinates and wind turbine specifications delivered by wind turbine manufacturers, which limits the bias from applying satellite image data, such as Google Earth, where the rotor diameter is undefinable due to the perspective of the images. For the above reasons this study provides an agnostic estimate of wind turbine spacing areas. The only source of error occurs for the conversion of coordinates and determining the actual center location of the wind turbine tower, which might involve an uncertainty of a few meters.

Some may argue that spacing area of a wind farm should be defined to include the space between clusters of turbines, such as in Fig. 3, because the addition of another turbine between clusters will reduce the power output among all turbines in the farm due to the competition among all turbines for available kinetic energy. However, regardless of how the spacing area (thus installed power density) is defined, the addition of a single turbine outside the defined spacing area will decrease the average output power density of a wind farm due to competition.

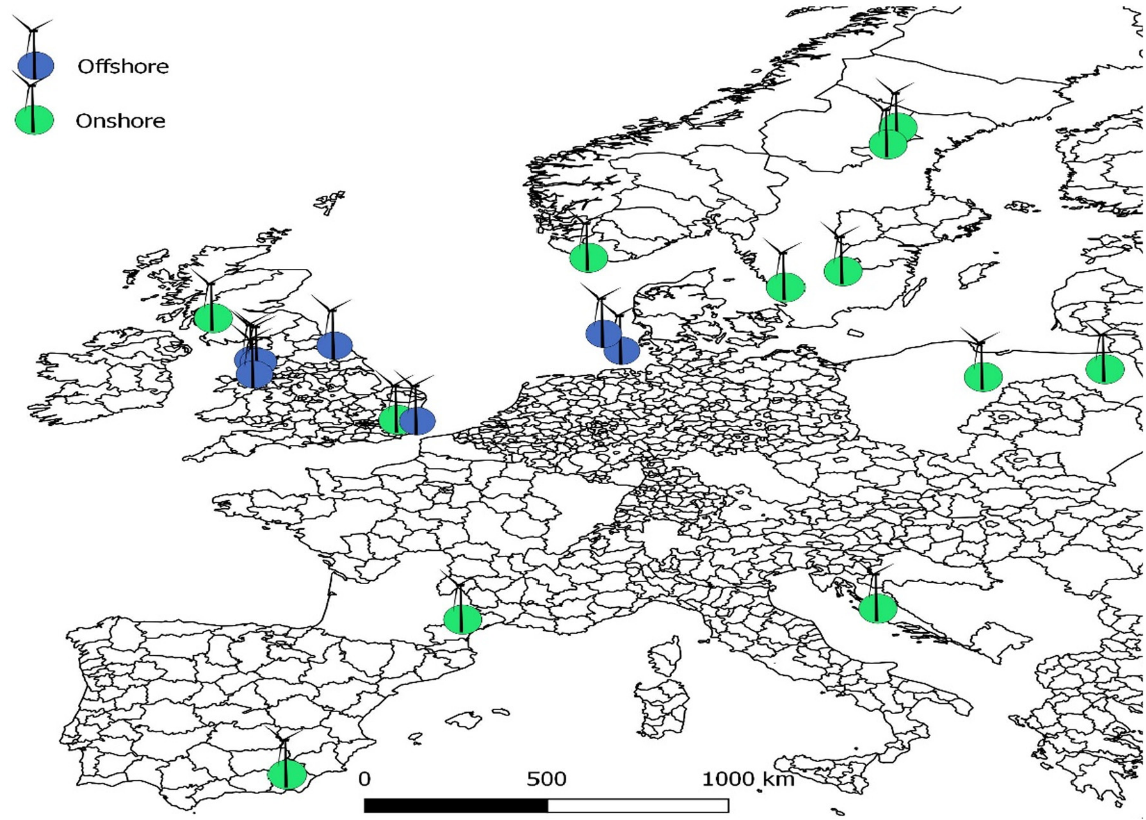

Fig. 5. Locations of the European wind farms examined.

For example, even if the spacing area were defined as a single large square box around all the turbines in Fig. 3, the addition of one more turbine outside the box would decrease the average output power density of all turbines inside the box. Thus, the addition of a turbine to a wind farm decreases average power output regardless of how the spacing area is defined.

The main conceptual difference between the method presented here and previous methods is that a spacing area calculated with the present method reflects near the minimum spacing area needed for a wind farm. Thus, the addition of a turbine to the farm always increases the spacing area required by the farm.

With previous methods, so much extraneous space exists between wind turbines in a farm and outside of the wind farm boundaries that many additional turbines can be added to the farm without increasing the spacing area. This artificially deflates both the installed and output power densities of wind farms in which turbines are spread apart or separated into clusters. In other words, a definition of spacing area that allows turbines to be added to a farm without increasing the spacing area of the farm incorrectly implies that a wind farm *needs* the entire spacing area assigned to it. Further, the fact that an additional wind turbine can be added to a wind farm without increasing the overall spacing area proves that the area occupied by the new turbine was not a necessary part of the spacing area of the original farm. With the definition proposed here, each wind farm needs most of the spacing area assigned to it, and each new turbine added to a wind farm increases the spacing area of the farm.

Wind farm data

The dataset presented here includes energy production from and characteristics of more than 1600 wind turbines in 13 countries, including 9 in Europe (Spain, Denmark, Portugal, Croatia, Poland, UK, Norway, Sweden, and Germany) and one in each of four other continents (China, Australia, the United States, and Chile). All output data are for wind turbines operating from 2016 to 2018. The dataset consists of the following information:

- Wind turbine data (nameplate capacity, rotor diameter, and hub height)
- Wind farm data (number of wind turbines and latitude/longitude of each turbine)
- Production data (hourly energy output from each wind turbine for 2017–2018)

All data used for this study were provided by several wind turbine manufacturers and developers who have requested to remain anonymous. The raw data without information identifying the location, manufacturers or developers are available upon request and are summarized in this paper.

The European data analyzed in this research are from 15 onshore wind farms and 11 offshore wind farms spread over nine European countries. Fig. 5 shows the locations of the wind farms.

The countries covered in this research include both mature and emerging markets, ranging from Germany (~60 GW installed capacity by the end of 2018) to Croatia (~0.6 GW installed capacity by the end of 2018) (WindEurope, 2019). The offshore wind farms applied in this study are all located in the North Sea, which holds the majority of the world's operating offshore wind farms. The micro-location of the majority of the wind farms are in rural areas, as this is the preferable target for new wind project development in mature and developing markets (Enevoldsen et al., 2018). However, one can expect urban areas to have an impact on wind turbine spacing given restrictions and social opposition (Enevoldsen & Sovacool, 2016).

Table 1 indicates that the mean (range) rotor diameter, nameplate capacity, and number per farm of the onshore European wind turbines used in this study are 105 (82–113) m, 2.59 (2.3–3.0) MW, and 32 (7–139), respectively. These turbines are powered by mean wind speeds

Table 1
Specifications of the 19 European wind farms considered in this study ranging from wind farms with 7 to 178 installed wind turbines, respectively. Data for wind speed were obtained for 2017 from wind farm owners.

Onshore					Offshore				
Location	Rotor diameter (m)	Wind turbine size (mw)	Number of wind turbines	Mean wind speed at hub height (m/s)	Location	Rotor diameter (m)	Wind turbine size (mw)	Number of wind turbines	Mean wind speed at hub height (m/s)
Denmark	117	3.45	11	8.7	Denmark	93	2.3	90	8.9
Denmark	117	3.6	9	7.7	Denmark	80	2	80	8.8
Denmark	113	3.2	22	8.2	Denmark	93	2.3	91	9.2
Spain	93	2.3	19	6	Denmark	120	3.6	111	9.1
Poland	108	2.3	22	6.8	UK	120	3.6	69	8.3
Croatia	101	3.0	17	6.6	UK	120	3.6	178	8.3
Poland	108	2.3	14	5.9	UK	93	2.3	28	7.3
UK	93	2.3	34	6.2	UK	120	3.6	52	8.9
Norway	93	2.3	34	7.6	UK	120	3.6	110	9.1
Sweden	101	2.3	33	7	Germany	120	3.6	79	9.9
Sweden	113	3.0	97	7.9	Germany	120	3.6	81	8.9
UK	93	2.3	131	6.6					
Sweden	113	3.0	15	6.3					
Sweden	101	2.3	12	6.1					
France	82.0	2.3	7	8.0					
Mean	105	2.6	32	7.04	Mean	109	3.1	88	8.8
Total			477		Total			969	

ranging from 5.9 m/s to 8.7 m/s, with a weighted average among all wind farms of 7.04 m/s.

The summed nameplate capacity of the onshore European wind turbines is 1231 MW and of the offshore turbines is 3088 MW.

Larger wind turbines power offshore than onshore wind farms. For offshore farms, the mean (range) rotor diameter is 109 (80–120) m and nameplate capacity is 3.1 (2.0–3.6) MW. The number of turbines per offshore farm ranges from 27 to 175, with a mean of 88. The mean offshore wind speed range is 7.3 m/s to 9.9 m/s, with a mean of the means of 8.8 m/s.

Results

Tables 2–4 summarize key results from this study. Tables 2 and 3 provide installed and output power density statistics derived from the method presented here for European onshore and offshore wind farms, respectively, and Table 4 provides statistics for onshore wind farms on four continents outside of Europe.

The mean (range) of installed power densities in Table 2 is 19.8 (6.2–46.9) MW/km^2. These numbers compare with mean (range) of previous estimates of 7.2 (1.5–13.6) MW/km^2 (Fig. 1), and although we find a high standard deviation, our standard error indicates that our wind farms are comparable. Thus, the mean installed power density from this study is 1.5 to 13 times the range from previous studies. As such, most previous studies appear to have significantly overestimated spacing requirement (thus underestimated installed power density) of onshore wind turbines compared with the European farms in Table 1. The same result holds true for the international farms examined in Table 4. This finding is important for future wind project development, as developers could deploy the same nameplate capacity of wind over less land than previous studies have indicated. Alternatively, space between clusters can be filled in as well with more turbines. The additional turbines will usually reduce the overall wind farm capacity factor slightly due to additional competition for available kinetic energy.

Therefore, we wanted to test such relationship for real operating wind farms in a comparable wind climate and with comparable market regulations to minimize the impact of variability in the decision making of the wind turbine spacing. However, when comparing different wind farms of different installed power density, the correlation between installed power density and capacity factor is not so clear. Fig. 6 shows capacity factors versus installed power density for nine onshore wind farms and four offshore wind farms in Denmark supporting the findings generated by the wind farms in Table 1, and further accessing 13 wind farms in a similar wind climate. The figure indicates that the capacity factors of some wind farms that have both a high nameplate capacity and high installed power density can exceed those of other wind farms with lower values of both. The reason is simply that one wind farm may have a better wind resource or turbine than another. Wind turbine technologies have improved over time which biases

Table 2
Summary statistics for the European onshore wind farms listed in Table 1.

Statistic	Spacing area per farm (km^2)	Number of turbines per km^2	Installed power density (MW/km^2)	2018-Average output power density W/m^2
Mean	8.1	7.0	19.8	6.64
Median	3.5	6.0	13.9	3.90
Standard error[a]	3.3	1.1	3.8	0.59
Standard deviation	12.3	3.9	14.4	1.93
Range	36.7	11.1	40.7	5.87
Minimum	0.8	2.4	6.2	2.30
Maximum	37.5	13.5	46.9	8.17

[a] The standard error is the standard deviation of the mean value. It is estimated as s/sqrt (n), where "s" is the standard deviation of the data sample, and "n" is the total number of observations. The outcome describes the accuracy of the mean.

Table 3
Summary statistics for the European offshore wind farms listed in Table 1.

Statistic	Spacing area per farm (km^2)	Number of turbines per km^2	Installed power density (MW/km^2)	2018-Average output power density W/m^2
Mean	50.0	2.6	7.2	2.94
Median	34.6	1.8	6.1	2.58
Standard error[a]	9.9	0.7	1.4	0.62
Standard deviation	32.7	2.2	4.5	1.65
Range	100.1	7.9	16.9	5.18
Minimum	3.1	0.9	3.3	1.15
Maximum	103.2	8.8	20.2	6.32

[a] The standard error is the standard deviation of the mean value. It is estimated following s/sqrt(n) and is a measure of the accuracy of the mean.

Table 4
Installed and output power densities for non-European onshore wind farms in 2018.

Wind farm	Spacing area per farm (km^2)	Number of turbines per farm	Number of turbines per km^2	Nameplate capacity of turbine (MW)	Installed power density MW/km^2	2018-Average output power density W/m^2
China	0.60	10	16.7	2.9	48	11.17
Australia	12.83	90	7.0	3.0	21	7.82
United States	4.54	43	9.5	2.3	21.7	6.60
Chile	6.98	50	7.2	2.3	16.5	4.81
Total or mean	24.95	193	7.7	2.66	20.5	6.84

benchmarking different farms (Enevoldsen & Xydis, 2019). Also, the siting of wind turbines depends just as much on topographical conditions, noise, and visual impact as it does on wake optimization (Enevoldsen, 2016; Enevoldsen et al., 2018).

Table 2 suggests a mean (range) of the annual-average output power density for European onshore turbines of 6.64 (2.3–8.2) W/m^2. The large standard deviation (1.93 W/m^2) implies a large diversity in the dataset, which indicates that various types of wind farm layouts have been covered. It could furthermore be driven by different wind turbine technologies installed to utilize local weather as well as support mechanisms (Enevoldsen, 2016). The resulting mean capacity factor of onshore European farms is 33.5%.

The high mean annual-average output power density for onshore European wind farms found here of 6.64 W/m^2, which is based on wind farm operator data, significantly exceeds the estimate of Miller et al. (2015), who argue that "the reduction of wind speeds and limited downward fluxes determine the limits in large-scale wind power generation to less than 1 W/m^2." The estimate from Miller et al. (2015) is similar to that from Bryce (2010), 1.2 W/m^2, and both are near half the 2 W/m^2 estimate from MacKay (2008) and greater than the 0.5 W/m^2 estimate from Miller and Keith (2018). Indeed, as the mean annual power output density for onshore European wind farms here averages more than 13 times 0.5 W/m^2.

The reasons for the low output power densities in the previous studies are twofold. First, several of those studies define installed power density incorrectly, as previously discussed, and output power density depends linearly on installed power density. Second, some previous studies, such as Miller et al. (2015) and Bryce (2010) assumed that wind farms are all packed close to each other. For example, Miller et al. (2015) assumed one large wind farm in Kansas over a region of 112,320 km^2. This area represents 52.7% of the land area of Kansas. No realistic wind farm will ever occupy that much space. For example, the spacing areas of the real European onshore wind farms examined here are a mean of 50 km^2 with a range of 3.1–100.1 km^2 (Table 1). The mean is only 0.045% the area assumed by Miller et al. (2015). Thus, Miller et al. (2015) unrealistically packed the wind farms together. They then assumed installed power densities of 0.3125 to 100 MW/km^2 over this large area. If one assumes that the installed power density is less than 2 MW/km^2, then it is physically impossible for the output power density to exceed 1 MW/km^2 (unless the capacity factor exceeds 50%), since the output power density equals the installed power density multiplied by the capacity factor. Thus, at the low end of the installed power densities assumed by Miller et al. (2015), it is physically impossible for the output power density to exceed 1 MW/km^2, so the result found by them is merely a function of their assumption, not a finding based on data. At the high end (2–100 MW/km^2), the area of the wind farm was so large that the nameplate capacity of turbines packed in the one wind farm skyrocketed up to 225 GW-11.2 TW. In those cases, all wind energy going through the farm was extracted by only a small subset of the turbines. No real wind farm would be built like this. As such, no case examined by Miller et al. (2015) was realistic.

Instead, in reality, wind farms are separated by distance and that allows higher output power densities to be achieved for the same high installed power densities assumed in Miller et al. (2015). This fact is illustrated perfectly in Fig. 2b of Jacobson and Archer (2012). The figure shows that spreading wind farms apart out over larger areas, without increasing the number of turbines or changing the installed power density inside of a wind farm, increases the aggregate power output among all farms. In other words, multiple wind farms will have a greater individual and aggregate output power density when the farms are spread apart from each other.

Table 3 indicates that, with the methodology presented here, European offshore wind turbines are spaced further apart within

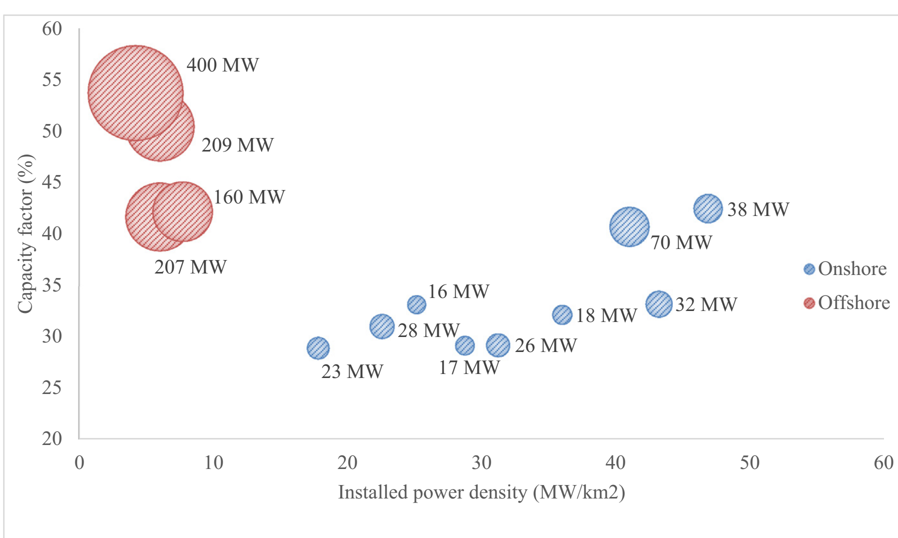

Fig. 6. The relationship between wind farm capacity factors (%) and installed power densities (MW/km^2). The size of the bubbles represents the installed nameplate capacity of the wind farm (MW). The 13 wind farms are all located in Denmark, and the capacity factor (%) is based upon the annual energy production in 2017.
Data were obtained from Energistyrelsen in Denmark providing monthly energy productions (MWh) for each wind turbine.

individual farms than are European onshore wind turbines, resulting in an offshore mean (range) installed power density of 7.2 (3.3–20.2) MW/km^2. This result is consistent with findings from Enevoldsen and Valentine (2016), who found that despite their larger nameplate capacities, offshore turbines are spread apart more than onshore turbines. The standard error furthermore indicates less spread in the sampling data as for the onshore wind farms. Prior studies (Fig. 2) not based on data have estimated a mean (range) installed power density of 7.6 (3–12) MW/km^2, which is close to the mean found from this study. However, the mean here is significantly larger than the mean of 3 MW/km^2 from U.S. D.O.E (2016), which has been relied on for policy decisions.

The mean (range) output power density for offshore farms here is 2.94 (1.15–6.32) W/m^2, which is again larger than a previous suggestion that wind farm output is limited to 1 W/m^2. The output power density here for offshore wind farms is similar to the estimate of 3 W/m^2 from MacKay (2008). The mean capacity factor of the offshore European turbines in Table 3 is 40.8%.

Comparison of installed power density among studies

Here, we examine differences between the present and past results for installed power densities. Denholm et al. (2009) and U.S. D.O.E (2015) found an average installed power density of 3 MW/km^2 and 2.9 MW/km^2 for onshore wind farms, respectively. This result suggests almost one wind turbine, instead of five, can typically be installed over the same land area, compared with the data-based result here. More land area required would mean a higher levelized cost of energy (LCOE) despite the lower competition among wind turbines for available kinetic energy due to spreading wind turbines apart. One reason for the low estimate in Denholm et al. (2009) is that they included "*land that was set aside for future project expansion and double counting of land where projects overlap*." The present study does not double count land, as stated in the Materials and methods section of this paper. Further, future projects are not included, as wind farm layouts tend to change several times before being constructed (Wizelius, 2015).

On the other end of the spectrum, Enevoldsen and Valentine (2016) estimated the mean installed power density for onshore wind turbines in non-forested areas as 13.6 MW/km^2, derived from estimated mean spacing for onshore non-forested and forested turbines of $4.375D \times 4.375D$, where $D = 100$ m is the rotor diameter for turbines of 2.6 MW nameplate capacity. Despite this rough estimate, the result is not substantially different from the European onshore wind installed power density of 19.8 MW/km^2 from this study (Table 2).

One outlier estimate of offshore installed power density is from U.S. D.O.E (2016), 3 MW/km^2. This number was proposed in order to "*adjust for greater array spacing, and to provide consistency with the Wind Vision*," where the *Wind Vision* is a target of an installed offshore wind capacity of 86 GW, which should equal an electricity production of 339 TWh in 2050. The higher average installed power density of 7.2 MW/km^2 for the offshore wind farms in Northern Europe found here (Table 3), indicates experienced offshore wind energy actors are deploying wind turbines with greater installed power density in order to lower the cost of electrical infrastructure, (19% of the combined cost for a turnkey offshore wind turbine (Heptonstall et al., 2012)) (Hou et al., 2015).

In the other extreme, EEA (2009) proposed an installed power density of 12 MW/km^2 for offshore wind farms in European waters in 2020.

Fig. 7. Comparative spacing areas required for the Bull Creek, Texas wind farm. The largest area represents the averaged installed power density of 1.5 MW/km^2 for all U.S. wind farms from Miller and Keith (2018). The second area represents the estimated installed power density for the Bull Creek farm of 3.3 MW/km^2 from Miller and Keith (2018). The shading area around the clusters represents the installed power density from the present study, 49.1 MW/km^2.

This is a greater installed power density than the empirical mean value of 7.9 MW/km^2 found here. One reason for the difference is that EEA (2009) assumed an increase in rotor diameter without increasing the spacing distance, thus calculated an artificially high installed power density. Enevoldsen and Valentine (2016), on the other hand, applied real operating offshore wind turbines with a mean nameplate capacity of 3.4 MW and a mean rotor diameter of 116 m to find an installed power density of 7 MW/km^2, similar to the mean data results found here, 7.2 MW/km^2 (Table 3).

Results for wind farms on four other continents

Table 4 provides additional results for single onshore wind farms in each China, Australia, the United States, and Chile. Each location is on a different continent (Asia, Australia, North America, and South America, respectively). The international locations were investigated to cover four continents, to examine the two countries with the highest installed capacity of wind power (the United States and China), and to look at data in two continents with promising wind project development patterns (South America and Australia). The wind farms were randomly picked.

The onshore wind farms in Australia, the United States, and Chile have similar installed power densities as the European onshore wind farm. The Chinese wind farm, on the other hand, has an extremely high installed power density, which is possible due to the relatively small rotor diameter of the turbines (93 m). The weighted-mean annual installed and output power densities of the four wind farms are 20.5 MW/km^2 and 6.84 W/m^2, respectively, which are both very close to respective values for onshore European wind farms (Table 2). The mean data-derived installed power density outside of Europe is up to 7 times that claimed in U.S. D.O.E (2015). The output power density is 3.4–6.8 times those claimed in Miller et al. (2015), Bryce (2010) and MacKay (2008). The mean capacity factor of the non-European onshore wind farms is 33.4%, which is almost the same as for the European onshore farms (33.5%).

Comparison with another method of determining wind turbine spacing

In this section, results from the method described herein are compared visually with those from another study. Recently, Miller and Keith (2018) used Voronoi polygons to estimate the installed power density of wind power at various sites in the United States, including the Bull Creek wind farm in Texas. That wind farm was not included as part of the original dataset in the present study (Table 4). However, we now evaluate it using the approach developed in this paper.

For Bull Creek, Miller and Keith (2018) estimated an installed power density of 3.3 MW/km^2 (180 MW over 54 km^2). For all wind farms they examined in the U.S., Miller and Keith (2018) further estimated an installed power density of 1.5 MW/km^2. Bull Creek was further used in a case study by Denholm et al. (2009) who according to Miller and

Fig. 8. Comparative spacing areas for the Gawlowice wind farm in Poland. The largest area represents the averaged installed power density of 1.5 MW/km^2 from Miller and Keith (2018). The second area represents the average installed power density of 7.2 MW/km^2 from all previous studies in Fig. 1, and the innermost shading represents 19.8 MW/km^{2,} which is the mean onshore installed power density for European wind farms from Table 2 of this study.
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Keith (2018), estimated an installed power density there of 0.74 MW/km^2 (180 MW over 243 km^2) for that site. The methodology from the present study gives an installed power density of 49.1 MW/km^2, which is higher than the average installed power density for the other modern onshore wind farms from this study (Tables 2 and 4). The reason is the close spacing within each cluster/row and the short rotor diameter (61.5 m) of each turbine in the Bull Creek farm. Fig. 7 compares the two spacing areas from Miller and Keith (2018) (those resulting from their U.S. average and Bull Creek installed power densities), with the spacing area based on the installed power density calculated here.

The three spacing areas (installed power densities) in Fig. 7 are 120 km^2 (1.5 MW/km^2), 54 km^2 (3.3 MW/km^2), and 3.6 km^2 (49.1 MW/km^2), respectively. The two larger spacing areas, from Miller and Keith (2018), substantially overestimate the land area required for this wind farm since they include large amounts of space outside the wind farm boundaries and include space between clusters of turbines, which in reality can be and is used for multiple purposes, such as farmland, grazing land, or open space. The problem lies in the methodology, which is to estimate a single-spacing area (in this case, a polygon) that is representative of all the wind turbines in the wind farm. Such a methodology results in errors because a) it does not consider that most wind farms have irregular shapes due to micro-siting issues, such as land restrictions and wake effects, thus they have clusters separated by distance; b) it includes large spacing areas outside the boundary of the wind farm where no wind turbines are installed; and c) it arbitrarily assumes that each wind turbine requires unrealistically large areas in all direction, thus it risks double counting overlapping areas assigned to adjacent turbines.

Fig. 8 illustrates the use of three different installed power densities to estimate the spacing area required of another onshore wind farm, Gawłowice, located in Poland. One density is the mean onshore installed power density of 1.5 MW/km^2 from Miller and Keith (2018). Another is the mean installed power density of 7.2 MW/km^2 from all previous studies (Fig. 1). The third is 19.8 MW/km^2, which is the mean onshore installed power density for modern European wind farms from Table 2 of this study.

As illustrated in Fig. 8, 19.8 MW/km^2 appears to be a conservative estimation for this particular wind farm.

The method developed for this study avoids all three problems that occur in Miller and Keith (2018) and several other studies. A reasonable question to ask, though, is whether the installed power density from the present study of, for example, the Bull Creek farm (49.1 MW/km^2) can merely be multiplied by the area of land available for any wind farm development to determine the maximum possible nameplate capacity of wind turbines that can be installed in the farm. The answer is technically, yes, since if all the rows of turbines in Fig. 6 were brought closer together so that no spacing area existed between rows, the turbine blades and towers would be separated by distance.

However, for practical purpose, the recommended installed power density for wind turbines is an average installed power density from either Tables 2–4, not one of the maximum values, which the installed power density in Fig. 7 is close to. Applying an average installed power density to the area of land developable for wind provides a reasonable estimate of the upper limit of the nameplate capacity of wind that should be installed in that area to achieve a reasonable capacity factor for wind.

However, using the mean value of the installed power density to estimate future installations may be conservative. Even densely-packed farms can have high power outputs (Enevoldsen et al., 2018). In 2015 an onshore wind farm "Klim" was commissioned in Denmark consisting of 22 Siemens Wind Power (Now Siemens Gamesa Renewable Energy) turbines. Fig. 9 illustrates the wind farm layout and its spacing area.

Based on the method used here, the Klim wind farm has an installed power density of 41 MW/km^2, which is at the high end of European wind farms. In 2016, the average capacity factor of the farm was 36.36%; in 2017, it was 40.68%, and in 2018, it was 25.25%. This indicates that modern wind turbines can perform well despite their high installed power densities. Interestingly, the study also demonstrates that existing methodologies have been misestimating land use for wind power implying too large areas for wind project development.

For offshore wind farms, the mean installed power density from previous studies was 8.36 MW/km^2, however, for European offshore wind farms, this study finds an installed power density of 7.2 MW/km^2. Fig. 10 examines Horns Rev 2 (2009) and Horns Rev 3 (2018). The illustrates the difference in wind farm layout and optimization over a decade.

Fig. 9. Wind farm layout for Klim in Denmark. The wind turbines are the SWT 3.2-113 with a rotor diameter of 113 m, an installed capacity of 3.2 MW, and a hub height 92.5 m. The transparent polygon indicates the wind farm land use, and the red circles shows the tip height distance according to the method introduced in this study. © Google Earth. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

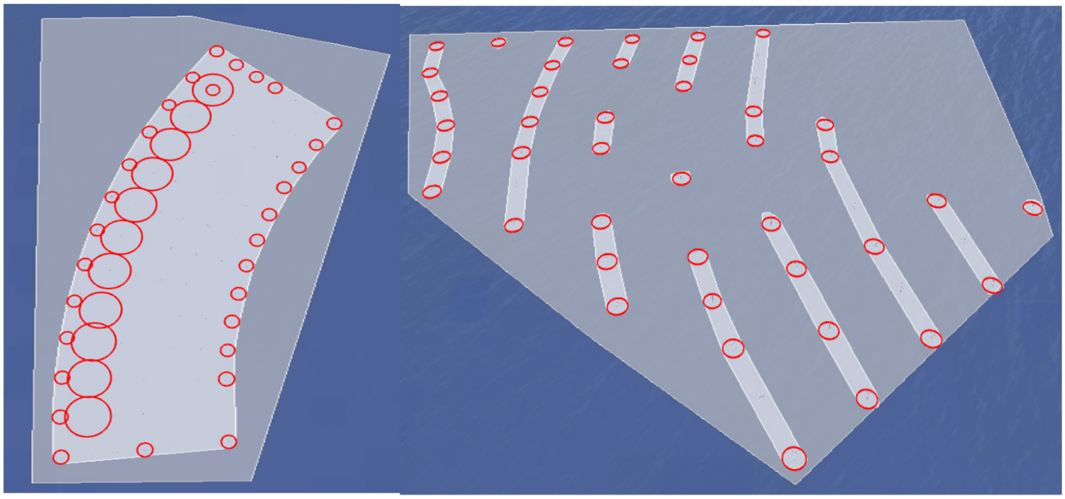

Fig. 10. Wind farm layouts for Horns Rev 2 (left) installed in 2009 and Horns Rev 3 (right) installed in 2018 in Denmark. The wind turbines in Horns Rev 2 are SWT 2.3-93 turbines, each with a rotor diameter of 93 m, a nameplate capacity of 2.3 MW, and a hub height 55 m. The wind turbines in Horns Rev 3 are V164-8.3 turbines, each with a rotor diameter of 164 m, a nameplate capacity of 8.3 MW, and a hub height 105 m. The small red circles indicate the tip height distance for each wind turbine, and the larger red circles represents that no additional tip distance is available between the wind turbines, why Horns Rev 2 must be considered as one cluster. The inner wind turbines in Horns Rev 2 have not been marked with circles, as they follow the same distance as between the first and second row. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) © Google Earth.

The large, outer polygons surrounding both wind farms in Fig. 10 represent an installed power density of 3 MW/km^2, as proposed by U.S. D.O.E (2016). The actual installed power density are the less transparent polygons, which give an installed power density of 6 MW/km^2 for Horns Rev 2, and an installed power density of 24 MW/km^2 for Horns Rev 3. The differences are because 1) Horns Rev 2 does not have more than three times the tip-height distance between the wind turbine rows, unlike Horns Rev 3 where this distances is exceeded in multiple places, and 2) the relationship between the wind turbines' nameplate capacity and tip height differs for each farm, with approximately 44 m/MW for Horns Rev 2 to 22.5 m/MW for Horns Rev 3. The two wind farms are also examples of offshore layouts that involves wake effects, electrical infrastructure costs, and to a minor degree for Horns Rev 3, visual impression.

Conclusion

This study uses an extensive dataset of more than 1600 operating multi-megawatt wind turbines across 5 continents to estimate spacing areas, thus the installed and output power densities, of onshore and offshore wind turbines over five continents. Because the spacing areas are based on wind farms that have already been built, they are not designed to provide the ideal distance between turbines for the planning of new farms. Instead, they are designed to be used to estimate how much land might be taken up with future wind development assuming that future installed power densities are the same as those of existing farms. The results are compared with those from 19 previous studies. The main conclusion is that previous studies have underestimated installed and output power densities of existing onshore wind farms. The main reasons are that such studies assumed spacing areas that erroneously included space outside of wind farm boundaries, space between clusters of turbines, and/or space already counted due to assuming large fixed spacing areas around each turbine.

In fact, for both European and non-European onshore wind farms examined here, the mean data-derived installed and output power densities are 1.5 to 13 times the range of estimates from previous studies. As such, for 8.33 TW of installed nameplate capacity to power 23.5% of 139 countries of the world for all purposes with onshore wind in 2050 (Jacobson et al., 2017), the land required (at 20 MW/km^2) may be only 417,000 km^2, or 0.35% of the 139-country land area, instead of up to 2.41%, as some studies assuming an installed density of 2.9 MW/km^2 have implied. For offshore farms, the data results here support and are in the range of some previous theoretical estimates of installed power density. Despite their high installed power densities, the onshore and offshore wind farms examined here have high capacity factors. The study thereby guides developers and project planners towards a standard for spacing density, within a range which does not impact the output density significantly. However, other factors might impact the wind farm layouts, why it is acknowledged that no uniform approach for layouts and thereby spacing densities exists.

In sum, this study contributes to analyzing the claim that existing onshore wind farms have low installed and output power densities. The main impact of the results here is that the large-scale development of onshore wind across the countries of the world may require significantly less land area than previous studies have estimated, which consequently equals more potential opportunities for new wind project development. This result also implies that the expected cost for new wind project development can be lowered, as this study found that wind turbines with less spacing performs just as well as others in a similar wind climate (Fig. 6), costs for electrical infrastructure and land acquisition which are two major costs in wind farm development (Heptonstall et al., 2012; Hou et al., 2017; Wizelius, 2015) can thereby be reduced.

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.

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