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Onshore wind energy atlas for the United States accounting for land use restrictions and wind speed thresholds

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ABSTRACT

The United States will need significant wind power to address climate change and air pollution. However, reaching proposed levels of wind installations sustainably and cost-effectively necessitates a better understanding of wind energy's land requirements. The objective of this study is to reduce the barriers to wind farm development by creating a high resolution, United States-wide onshore wind atlas. The atlas provides wind speeds 100 m above ground level and accounts for the following restrictions: buildings, roads, railways, waterways, water, land use types, and existing wind turbines. Results indicate that 63% (5,852,000 km^2, or 73 TW of nameplate capacity) of U.S. land area is unrestricted for wind farm development at wind speeds of 0 m/s and higher, and 27% (2,539,000 km^2, or 32 TW) is available at wind speeds of 6 m/s and higher. This is sufficient to provide all-purpose 2050 U.S. energy with wind. The five states with the largest wind potential at 6 m/s or greater are Alaska, Texas, Montana, Nebraska, and South Dakota. The atlas will not only allow policymakers and wind farm developers to make more informed decisions, but it will also reduce the time, cost, and uncertainty of wind farm development, accelerating the transition to 100% clean, renewable energy.

1. Introduction

In the coming years, it will be necessary for the United States to entirely decarbonize its economy in order to mitigate its climate impact as the second largest emitter internationally [1]. This will require a complete transition of the energy sector toward renewable resources such as wind and solar, hydroelectric, and geothermal energy, as well as energy efficiency, demand response, and energy storage. Onshore wind energy plays a significant role and will ideally provide 31.4% of the United States' energy and 30.5% of the world's energy by 2050 [2].

U.S. electricity consumption in 2020 was 3.8 trillion kWh [3], with 20% generated by renewables and 8.4% coming from wind power [4]. Multiple studies have recognized global wind power as a critical enabler for achieving 100% renewable energy penetration on the grounds that wind energy has immense technical potential to deliver useful electricity and energy services [5–7]. Previous estimates of U.S. wind power potential indicate that a quarter of the country is suitable for providing electric power from wind at a direct cost equal to that from a new natural gas or coal power plant [8]. Furthermore, Jacobson et al. estimated that the 2050 U.S. demand would possibly require 31.4% of its energy consumption from onshore wind power, or an installed onshore wind power capacity of 982.5 GW operating with a mean capacity factor of 31.7% [9]. This would be a significant growth from the existing 110 GW in 2020 [10]. Some researchers have suggested that installed wind power densities are so low that it would not be possible to capture sufficient power to meet the needs for a clean, renewable energy future in most countries, including in the U.S [11–13]. However, Enevoldsen and Jacobson found that, when using a method that considers the real shapes and land use of wind farms, the mean (range) installed and output power densities of onshore wind farms outside of Europe are 20.5 (16.5–48) MW/km^2 and 6.84 (4.81–11.2) W/m^2, respectively, indicating a higher density than previously estimated [14].

Wind farms can compete with, and sometimes complement, other land uses [13,15]. The land underneath the rotors and in

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between turbines can be used for agriculture, ranching, forestry, open space, and solar panels [16]. On the other hand, wind farms compete with recreation grounds, nature reserves, military areas, quarries, allotments, and cemeteries. Social opposition to onshore wind turbines is primarily directed at noise emissions and the visual impact around these spaces [17]. While measuring public opinion is complex [18], [–] [21] studies have found that most turbine neighbors have positive attitudes toward onshore wind power [22–26].

The U.S has experienced an unprecedented growth of wind installations [27], with wind energy accounting for 39% of all new U.S. generation in 2019 [28]. This is due in part to lower costs and state policies such as Renewable Portfolio Standards (RPS). Bills like California's SB 100 accelerate the state's renewable electricity goal to 60% by 2030 and will require the next 40% to come from zero-carbon sources of electricity by 2045 [29]. Despite this, the share of renewable energy in electricity generation is quite low, with the U.S. share of renewables in power generation ranking eighth lowest among the International Energy Agency (IEA) member countries [30]. Although not every state currently has an ambitious renewable energy goal, state and local governments are continuously increasing the levels of renewable energy that they mandate or aim to achieve.

One immediate challenge for the wind power expansion in the U.S. is the scoping of prosperous sites the first time [31,32]. Doing so will limit local siting risks and costs associated with feasibility studies [33]. While virtual maps like the National Renewable Energy Laboratory (NREL) Wind Prospector map [34] and the Global Wind Atlas [35] have been launched for the U.S., they supply information for wind flow modelling instead of high-resolution insights about available land. Meanwhile, maps based on land use are either focused on only one portion of the U.S. (Bureau of Land Management West-wide Wind Mapping Project [36]), have coarse resolution and few land restriction layers (United States Geological Survey Smart Energy [37]), include only information about natural and protected areas (The Nature Conservancy Site Wind Right [38]), or exclude the U.S. entirely (NREL RE Data Explorer [39]). In most cases, these maps do not include clear indications of whether restrictions were considered with additional protective boundaries, often omit important infrastructure, such as urban areas, lack flexibility in parsing layers, particularly different wind speeds, and/or are done at resolutions lower than here.

Historically, wind atlases have focused on lower hub heights and only considered the wind regimes, rather than including land and infrastructural restrictions. Wind resources have been mapped for the United States for several decades. One prominent example is the map by the Pacific Northwest Laboratory (PNL), published in 1986, which lists wind resource statistics for over 1,000 locations, with twelve regional assessments and varying levels of detail. However, these results are based on extrapolation from measurement sites, and could not capture the nuance that today's datasets contain. Furthermore, the scope is limited to the contiguous U.S., rather than including Alaska and Hawaii, which have the greatest resource potential and arguably the greatest need for wind energy, respectively [8,40]. Later on, wind resource estimates were made based on a combination of surface station observation data, upper-air observation data, and model-derived upper air data, which until relatively recently, had been focused on lower hub heights [41]. It was not until the early 2000's that wind maps exhibited resource estimates for higher than 50 m, with that developed by NREL and AWS Truepower being one of the most influential, featuring resource potential maps at 80 m and 100 m heights. However, spatial resolution was still limited to 200 m, which meant that despite the inclusion of rudimentary exclusion zones, such as urban areas, airports, and sensitive lands, the data was too coarse for detailed decision-making [42–44]. This was a vast improvement over the 1 km resolution used in 2001, and the 25 km resolution used in the late 1980's [41].

All of these limitations are addressed by this study. Wind potential estimates are dynamic, varying based on geography, wind technology, and siting considerations. This research follows the design principles from previous regional, national, and continental wind energy planning studies [15,32,45–49] in order to inform macro-siting of onshore wind turbines through geographical, infrastructural, and technical restrictions with setback distance requirements that were chosen to reflect pragmatic measurements of social opposition to deployment of a given wind technology [21,33]. Moreover, this study presents data inputs and analysis with maps consisting of higher spatial resolutions and multi-layers, allowing for the quantification of onshore wind energy potential and estimated capacity factors at a county level. The framework employed reflects the nature of real onshore wind farm planning by utilizing insight from actual projects [14] and converting industry knowledge into Geographic Information System (GIS) methodologies instead of applying theoretical exclusion zones as seen in Ryberg et al. [50] The approach of utilizing high-resolution open data sources has not been previously implemented in other studies, such as in McKenna et al. [51] or Bosch et al. [52] Other studies that rely on similar data sources have not highlighted the United States specifically, such as Chu et al. [53], or focused their scope of investigation to mapping the footprint of already-existing renewable energy generating locations, rather than developing a map that will assist with future planning, as this study aims to do [54]. This study also applies an uncommon level of detail in capacity factor calculations for macroscale examinations, which are tailored for each state and used to inform potential energy output (TWh) along with output power and energy density (MW/km^2 and TWh/km^2). Further, it uses varying wind speed thresholds from 0 to 10 m/s at which all metrics are calculated, compared with the approach used in Lopez et al. [48], which does not include this as a lever for analysis upon which subsequent economic decisions can be made.

The output here includes maximum available land area, wind turbine nameplate capacity (GW), energy output (TWh), nameplate capacity compared with population (people per potential MW), output power density (MW/km^2), and output energy density (TWh/km^2) for each U.S. state and county and the United States as a whole at seven different wind speed thresholds and three different turbine technologies, along with comparisons of some of these metrics with 2050 targets and 2018 consumption. The study also presents a series of maps and visualizations for all different scenarios at a 10 m resolution that can be used to make local decisions across the entire country. Finally, it provides the potential nameplate capacity of wind turbines relative to what is needed to power each U.S. state with its estimated portion of wind if the U.S. is transitioned to 100% clean, renewable energy for all energy purposes by 2050. When combined as an atlas, all these features can speed up the wind development process by reducing time in the macro-siting stage, which is typically the longest of any stage in the development, from three months down to one day [55].

This study draws insights from energy engineering, economics, geographic information systems, law, and policy to inform the onshore United States siting process and generate methods that can later be applied to other mapping efforts internationally.

2. Methods

Fig. 1 summarizes the methodology we used to create the wind atlas data presented here. The supplemental information describes each component of the methodology in detail.

A key requirement of siting wind turbines is that they must be kept beyond a minimum distance from infrastructure and buildings to

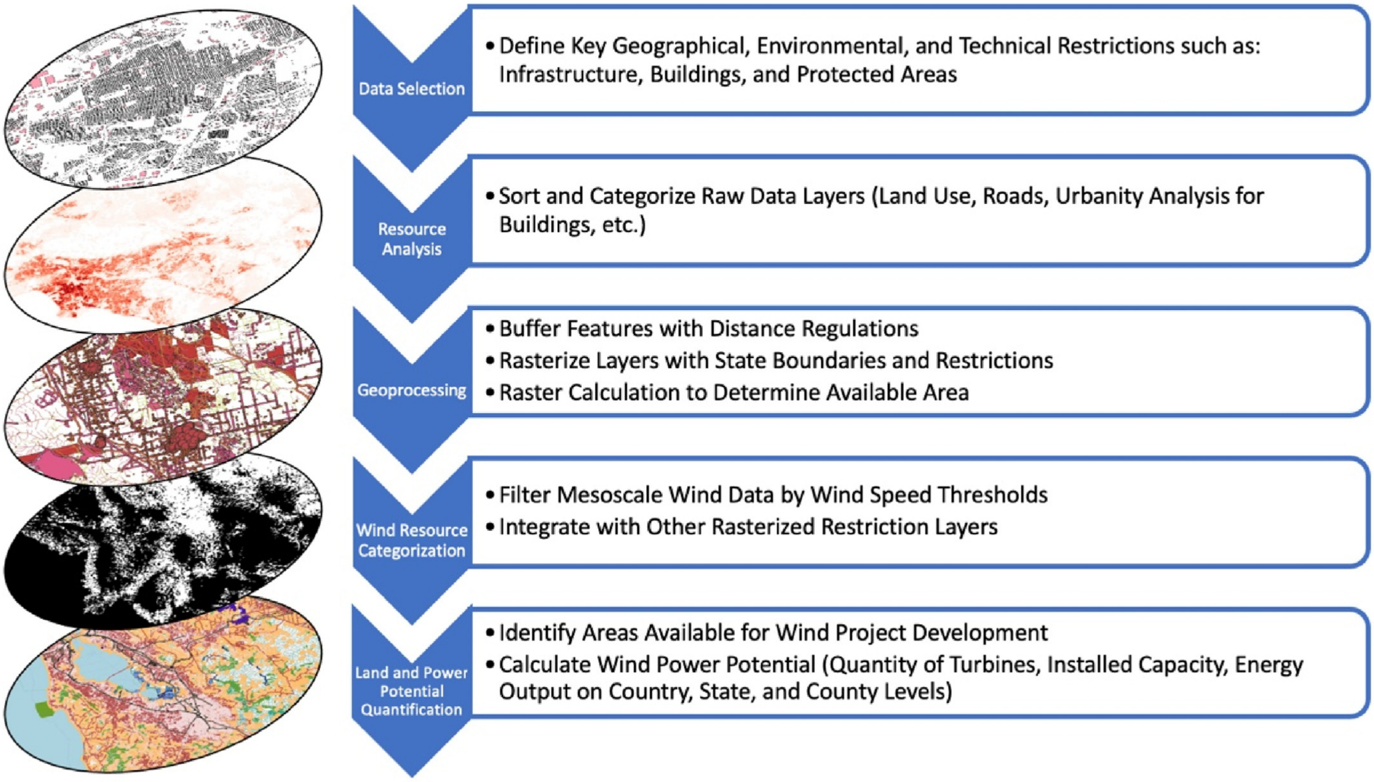

Fig. 1. The Process of Constructing a Wind Energy Atlas for the United States. Restrictions were categorized, processed, and analyzed using these steps in QGIS. See the supplementary information for details of each step.

maximize safety and minimize noise. The minimum distance from buildings is one of the most important restrictions, since it can trigger social opposition and stop the development of wind projects [45]. For most infrastructural restrictions, we used a buffer distance of at least 1.1 times the average turbine tip height, or 170 m, which is a common minimum across the United States due to the risk of damage from debris in case of a wind turbine's collapse, or from a blade throwing ice. Buildings were separated into urban and rural categories to buffer buildings in urban areas with a larger minimum distance.

In addition to infrastructure and buildings, we excluded certain land use classes, including allotments, cemeteries, military land, nature reserves, quarries, and recreation grounds, from developable land. Furthermore, existing wind turbines for each state are excluded and buffered using 170 m, based on the observation that many existing wind turbines are already built this close to infrastructure. Roads are sorted according to major (highways, motorways, residential streets, etc.) and minor (pedestrian routes, bike routes, etc.) to differentiate between features that require a buffer of 170 m and those that are not consequential enough to require a buffer, respectively. Similarly, waterways are sorted into navigable (rivers and canals) and non-navigable (streams and drains) to buffer only the features that would have regulations around wind turbine proximity.

Throughout the analysis, we created layers that represent the areas that pose restrictions for wind farm development with the goal of having a map of unsuitable areas for development, the area of which was calculated and subtracted from the total state area, defined by the state border layer.

Table 1 summarizes all the restrictions, buffer distances, and sources.

Table 1
Summary of Restriction Layers, Buffer Distances, and Data Sources.

Restriction	Description	Buffer Distance	Source
Buildings	Includes urban and rural (residential, industrial, military, public)	800 m for urban, 170 m for rural	U.S. Building Footprints - Bing Maps [56]
Major Roads	Highways, motorways, residential streets, and other major routes	170 m	OpenStreetMap - Geofabrik.de [57]
Minor Roads	Pedestrian routes, bike routes, and other minor routes	None	OpenStreetMap - Geofabrik.de
Railways		170 m	OpenStreetMap - Geofabrik.de
Navigable Waterways	Rivers and canals	170 m	OpenStreetMap - Geofabrik.de
Non-navigable Waterways	Streams and drains	None	OpenStreetMap - Geofabrik.de
Water		None	OpenStreetMap - Geofabrik.de
Land use	Includes recreation grounds, nature reserves, military areas, quarries, allotments, and cemeteries	None	OpenStreetMap - Geofabrik.de
Existing Wind Turbines	Includes locations of all land-based wind turbines and technical specifications	170 m (4.375 times turbine rotor diameter for spacing density)	United States Wind Turbine Database [58]
Wind Speed	Thresholds for wind speed ranging from 5 m/s-10 m/s	N/A	Global Wind Atlas [35]
Borders	Country, state, and county borders	N/A	U.S. Census Bureau [59]

After buffering all the restrictions described in Table 1, we proceeded to rasterize each layer of each state to facilitate the calculation. Each vector file was converted into a 10 m × 10 m resolution raster using the Rasterize tool in QGIS. The conversion from vector to raster does not result in significant data loss (a first order approximation reveals 99.9% matching areas). The visual result of this process is shown in Fig. 2, which highlights the transformation from buffered to rasterized data for California and the San Francisco Bay Area.

As a next step, mesoscale wind speed data was incorporated from the Global Wind Atlas [60], which has a 250 m horizontal resolution and is derived by downscaling the ERA5 dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) [61] at five different heights. A height of 100 m above ground level (AGL) was selected as the most representative hub height of a modern wind turbine.

As seen in Fig. 3, the analysis was replicated for each wind speed from 5 m/s to 10 m/s, at 1 m/s intervals, to obtain a series of minimum threshold layers that were later applied to a map of infrastructure and land use restrictions. This can be used to estimate the output power density for each state, as well as to determine the level at which a new development might be economical.

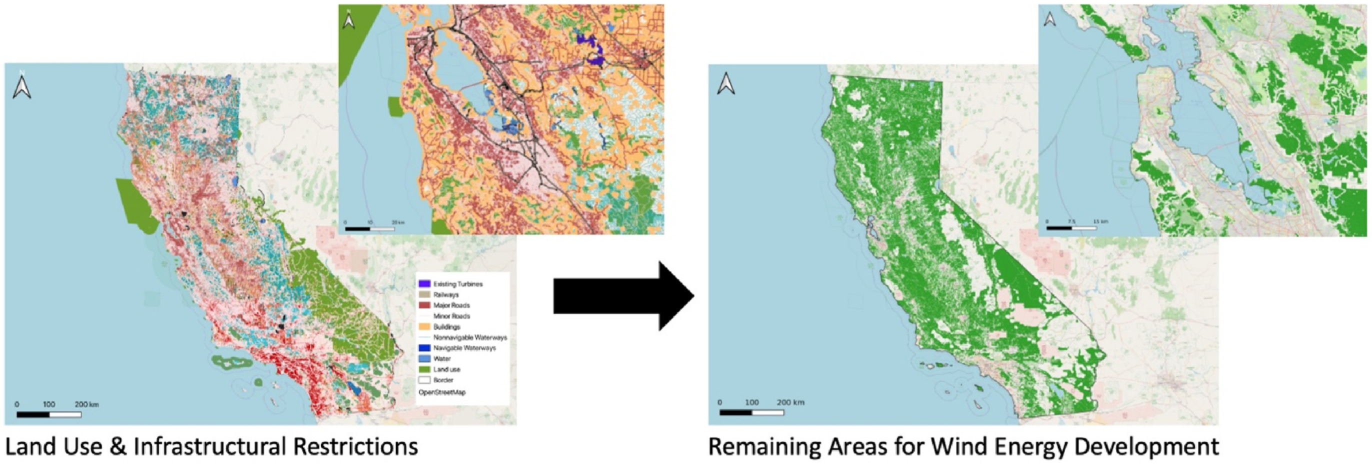

Fig. 2. Buffered California and San Francisco Bay Area Maps Transformed into Rasterized Maps. These maps show the process of transforming the buffered data, with most restriction layers displayed, into rasterized areas. On the right, the land in green represents available areas for wind farm development at any wind speed, while the rest is restricted. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

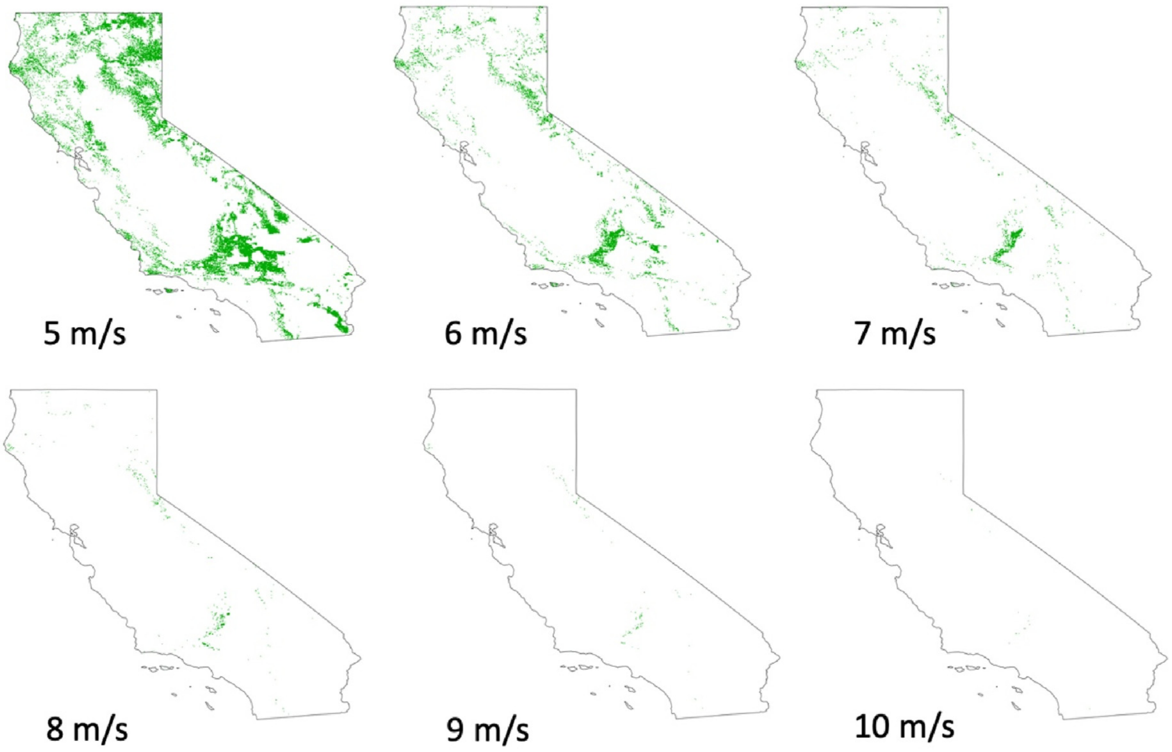

Fig. 3. Sequence of Increasing Wind Speed Restriction Thresholds for California. Wind speed restriction layers are shown with different wind speed thresholds. With increasing wind speed thresholds, the amount of available (green) area decreases. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Finally, the remaining area was calculated by subtracting each restriction layer from the border layer using the Raster Calculator. The Raster Layer Statistics tool was then used to sum the number of available cells, representing the total available and viable area for wind farm development.

After determining how much land area is available in each state, we calculated wind potential based on different wind speed thresholds, along with other useful metrics for decision-making, such as the number of turbines that can be installed, the people per potential megawatt, and the energy output (TWh), both with and without array losses, or wake effects from other nearby turbines. Then, after accounting for capacity factor, which was calculated for each state, other metrics such as output power density (MW/km^2) and the output energy density (TWh/km^2), were estimated and visualized.

3. Results

The estimated overall land area that is available for wind energy development after applying all restrictions except wind speed is 5.85 Mkm^2, as seen in Table 2. Compared with the total U.S. area of 9.36 Mkm^2, this represents 62.5% of the country's onshore land area. Then, if annual average wind speed thresholds of 5, 6, 7, 8, 9, and 10 m/s (at a 100 m hub height for all states) are applied, we find that the overall remaining area is reduced to 4.14 Mkm^2 (44.2%), 2.54 Mkm^2 (27.1%), 1.09 Mkm^2 (11.6%), 0.2 Mkm^2 (2.2%), 0.09 Mkm^2 (0.9%), and 0.04 Mkm^2 (0.5%), respectively.

There is an abundant amount of untapped wind potential and more than enough land area to meet energy demand and targets at most wind speeds, even without the substantial contribution Alaska makes. Because Alaska is unconnected from the continental U.S. power grids and there is not enough demand to meet supply in Alaska alone, it is useful to consider all U.S. states plus Washington, D.C. without Alaska. If Alaska is excluded, the remaining area for the contiguous U.S. states and Hawaii is reduced to 4.76 Mkm^2, or 60.6% of all available onshore area. The resulting overall country values can be found in Table 2 and results for each individual U.S. state can be found in terms of percentage in Fig. 4b.

Fig. 4a shows unrestricted land for wind energy development regardless of wind speed. This figure gives a high-level overview of where new wind turbines could be installed after considering all infrastructure and land use restrictions. The available land decreases further when wind speed thresholds are applied. The available areas are calculated using annual average wind speeds, which are not necessarily representative of local microscale wind patterns that might or might not make a site economical. Furthermore, high annual wind speeds (>7 m/s) are no longer necessary to make a site economically viable, as modern wind turbines are often cost effective at lower wind speeds (6–7 m/s) due to the relatively high increase in rotor diameters [63].

Fig. 4b shows the percentage of land area remaining for wind energy development after considering all restrictions except for wind speed. This map therefore shows the maximum percentage of available land for wind energy development. The barriers posed by restrictions are not uniform in every state. The distribution of protected areas, roads, railways, and other infrastructure are important factors. The percentage of available land tends to be highest in several western states and Alaska due to the large state areas and relatively low density of infrastructural buildout. Louisiana and Alabama also have a high percentage of available land, however, low wind speeds in these states will limit growth there. States in red have the highest percentage of available land area, with Wyoming having the highest at 79.8%. Densely populated northeastern states are among those with the least leftover area, with the lowest (besides Washington D.C.) being Massachusetts at 17.8%.

Fig. 5 shows the results for a single state, both in buffered and rasterized form, along with key metrics, including the area of land available for wind energy development, the potential nameplate capacity that can be generated in the state, and the turbine density relative to population. It is illustrative to show how prominent features like roads, cities, and water bodies are eliminated from the viable development area, which is represented by the colored pixels in Fig. 5b. Further, higher wind speeds, represented by darker red areas, will translate to places of higher potential for wind development. Each of the elements in this graphic are explored in more depth and analyzed across all states in the figures below.

Many states are currently far from meeting the onshore wind portion of their 2050 installed nameplate onshore wind capacity targets, obtained from Jacobson et al. [65] Most states are still less

Table 2

Overview of Results for United States and United States Excluding Alaska. All metrics, including land area remaining (km^2 and %), potential nameplate capacity (TW), installed power density (MW/km^2), and output power density (MW/km^2) are shown with no wind speed threshold (0 m/s) and the 6 m/s wind speed threshold.

Metric		Wind Speed Threshold	United States	Excluding Alaska
[a] Land Area Remaining (km^2)		0 m/s	5,851,573 (63%)	4,755,356 (61%)
		6 m/s	2,538,747 (27%)	1,997,365 (25%)
[b] Potential Nameplate Capacity (TW)	Without array losses	0 m/s	73	59
	With array losses		68	55
	Without array losses	6 m/s	32	25
	With array losses		30	23
[c] Installed Power Density (MW/km^2)	Low	Any	12.4	12.4
	High		20.5 (16.5–48)	20.5 (16.5–48)
[d] Output Power Density (MW/km^2)	Without array losses	0 m/s	4.03	4.02
	With array losses		3.75	3.74
	Without array losses	6 m/s	4.74	4.72
	With array losses		4.41	4.39

[a] Land area remaining is calculated after accounting for all restrictions, plus a 6 m/s wind speed threshold. These restrictions include buildings, major roads, minor roads, railways, navigable waterways, non-navigable waterways, water, land-use, and existing wind turbines (see Table 1 for details about each restriction layer).

[b] Potential nameplate capacity is the nameplate capacity which can be realized if SG 5.0–145 turbines are installed in all available land area. It is calculated using Equation S2 and is aggregated across all states. When accounting for array losses, which arise due to the competition among turbines for limited kinetic energy, a uniform 7% loss is applied [62].

[c] The low estimate of installed power density is turbine nameplate capacity divided by turbine spacing density, as defined in Equation S1. The high estimate is taken from Enevoldsen and Jacobson, which computed the mean installed power density of onshore wind farms outside of Europe [14].

[d] Output power density is calculated using the low estimate of installed power density multiplied by the capacity factor, averaged across states (32.5% and 32.4%, respectively, for 0 m/s wind speed threshold and 38.2% and 38.1%, respectively, for 6 m/s wind speed threshold). This value is calculated for the U.S. with and without Alaska, using SG 5.0–145 turbines after accounting for all infrastructure and land-use restrictions. A 7% array loss is applied.

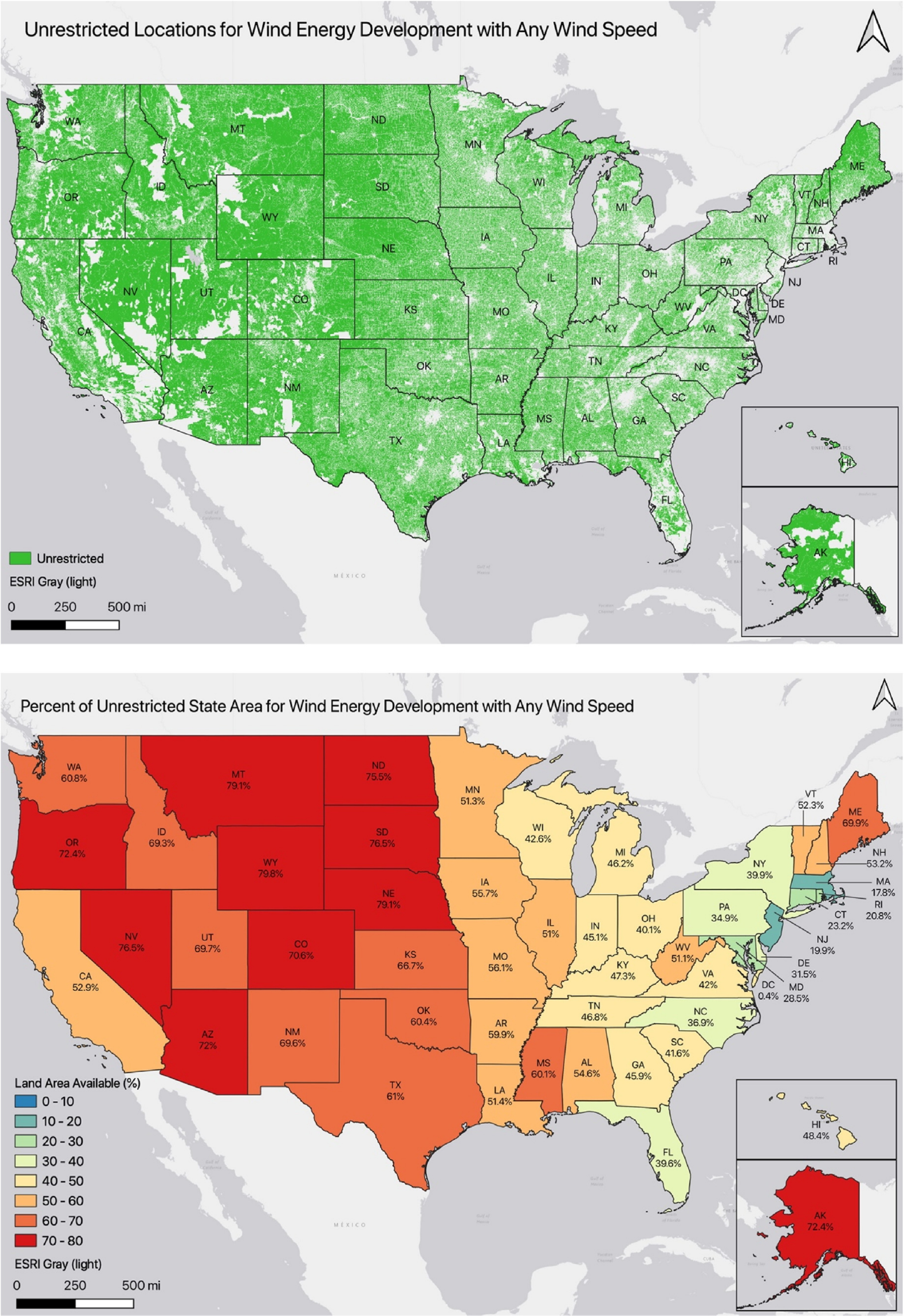

Fig. 4. Unrestricted Locations & Percent of Unrestricted State Area for Wind Energy Development with Any Wind Speed.
(a) Land areas for wind energy development are shown in green after accounting for all restrictions except for wind speed. The restrictions include buildings, major roads, minor roads, railways, navigable waterways, non-navigable waterways, water, land-use, and existing wind turbines. Table 1 provides details about each restriction layer. In total, 62.5% of U.S. land area is unrestricted. Similar maps, but with non-zero wind speed cutoffs can be found in Figures S1.1-S1.7.
(b) Land area available for wind energy development is shown as a percentage of the total area for each state. All restrictions are considered except wind speed. See Table S1 and Figures S2.1-S2.7 for additional maps in which this calculation is carried out. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

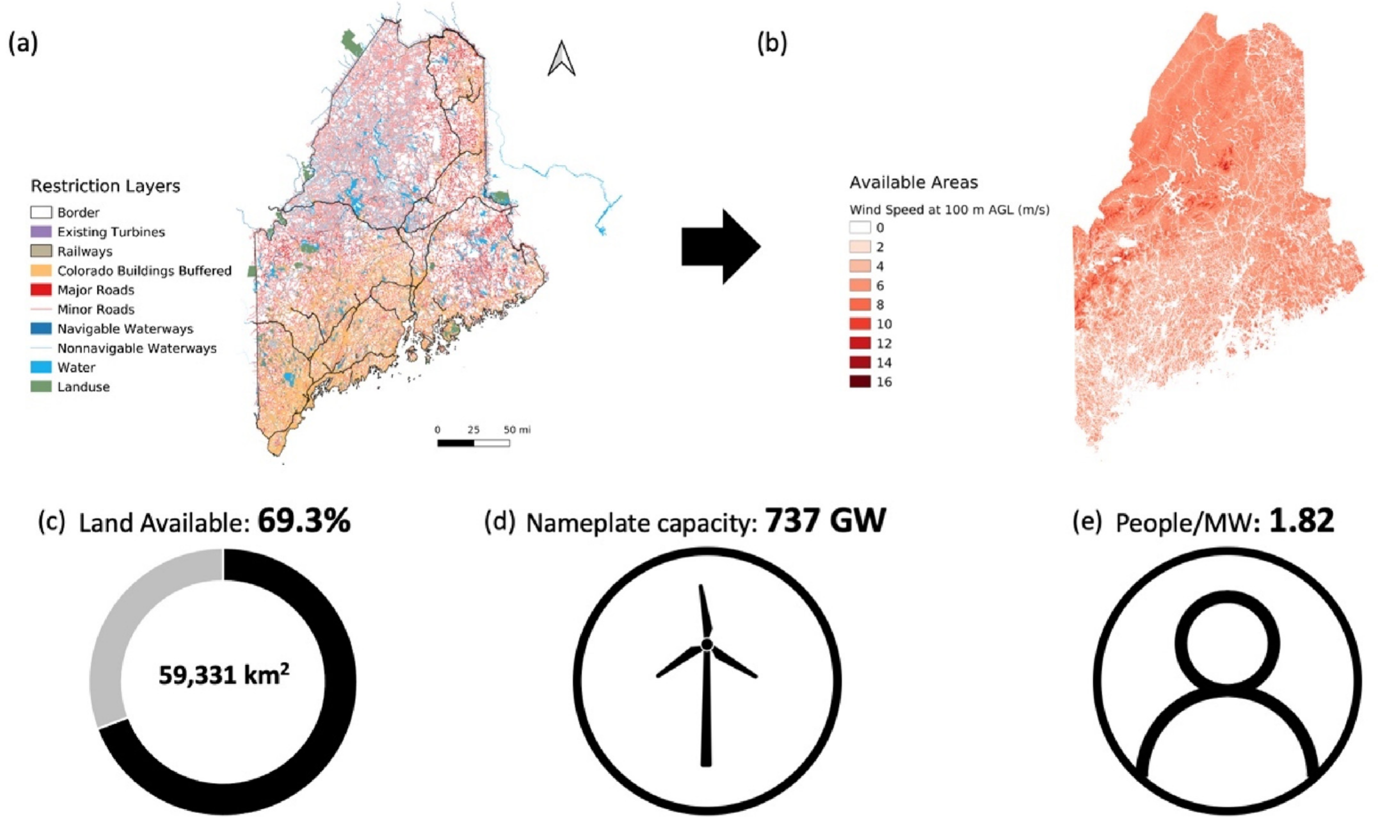

Fig. 5. Results Overview of Maine.

(a) Restrictions in buffered form, including buildings, major roads, minor roads, railways, navigable waterways, non-navigable waterways, water, land-use, and existing wind turbines. See Table 1 for details about each restriction layer.

(b) Available areas after accounting for every infrastructure and land-use restriction except wind speed in rasterized form, where color gradient shows mean annual wind speed at 100 m AGL (m/s) in each pixel.

(c) Area and percentage of available land for wind energy development when all restrictions except wind speed are considered.

(d) Potential nameplate capacity (GW) that can be realized if SG 5.0–145 turbines are installed in all available land area calculated using Equation S1 to find N_{turb}, multiplied by turbine nameplate capacity.

(e) 2019 state population [64] relative to potential installed nameplate capacity (MW) that can be realized if SG 5.0–145 turbines are installed in all available land area. Potential installed nameplate capacity is calculated using Equation S1 to find N_{turb}, multiplied by turbine nameplate capacity after accounting for all infrastructure and land-use restrictions except wind speed. The ratio of People/MW represents turbine density, or how many inhabitants there are relative to 1 MW. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

than 15% of the way to meeting their targets, and even the front-runner, North Dakota, has only 29% of the wind capacity it will need by 2050 (see Figure S10.1 for map).

When comparing the wind power potential by state derived from this study with 2050 wind energy targets, it becomes clear that most states have many times more potential to generate wind power than required, and far more than the capacity than is currently installed. Fig. 6 shows that the maximum ratio between the potential capacity and the 2050 target [65] occurs in Alaska, where there is 488 times more energy that could be produced than would be required to fulfill the wind portion of 2050 targets to meet end-use energy demand. Even the states with the smallest ratio of three, Massachusetts and New Jersey, could produce three times as much energy from wind as required to satisfy 2050 targets.

The states with the largest potential capacities are Alaska, Texas, Montana, Wyoming, New Mexico, Nebraska, South Dakota, Kansas, North Dakota, and Colorado, which all have over 1,500 GW of potential nameplate capacity when a 5 m/s wind speed threshold is applied. However, all states have more potential capacity than is necessary to meet 2050 targets.

In Fig. 7, we can see that most states consume far less energy annually than they would be able to produce from wind farms, without even including other kinds of renewable energy. There are only a handful of states (those in red) that consume more energy than could be produced from wind alone. Unsurprisingly, these are states with the highest populations, such as California, or smallest land areas, such as Connecticut. In these states, it will be necessary to rely on a mix of renewable resources. Alternatively, repowering outdated turbines can be a viable option in some places to increase the power output without increasing the footprint of generation (see Methods in supplemental information for details). It is also important to note that this map assumes each state would need to be self-sufficient and entirely meet demand with only in-state resources. In reality, many states are connected by larger grids that would allow for the benefits of transmission across state borders.

The potential output power densities in Fig. 8 were calculated by multiplying potential nameplate capacities by the capacity factor of wind in each respective state and turbine scenario, all divided by the remaining area of each wind speed threshold. Rather than relying on a uniform capacity factor, the capacity factor of each state was calculated using power curves and validated against real data. States such as South Dakota, Nebraska, and Kansas have potential output power densities above 5.6 MW/km^2, translating to the greatest potential for future wind power density. Compared with the U.S.-wide average output power density of 4.74 MW/km^2 at wind speeds above 6 m/s (without accounting for array losses),

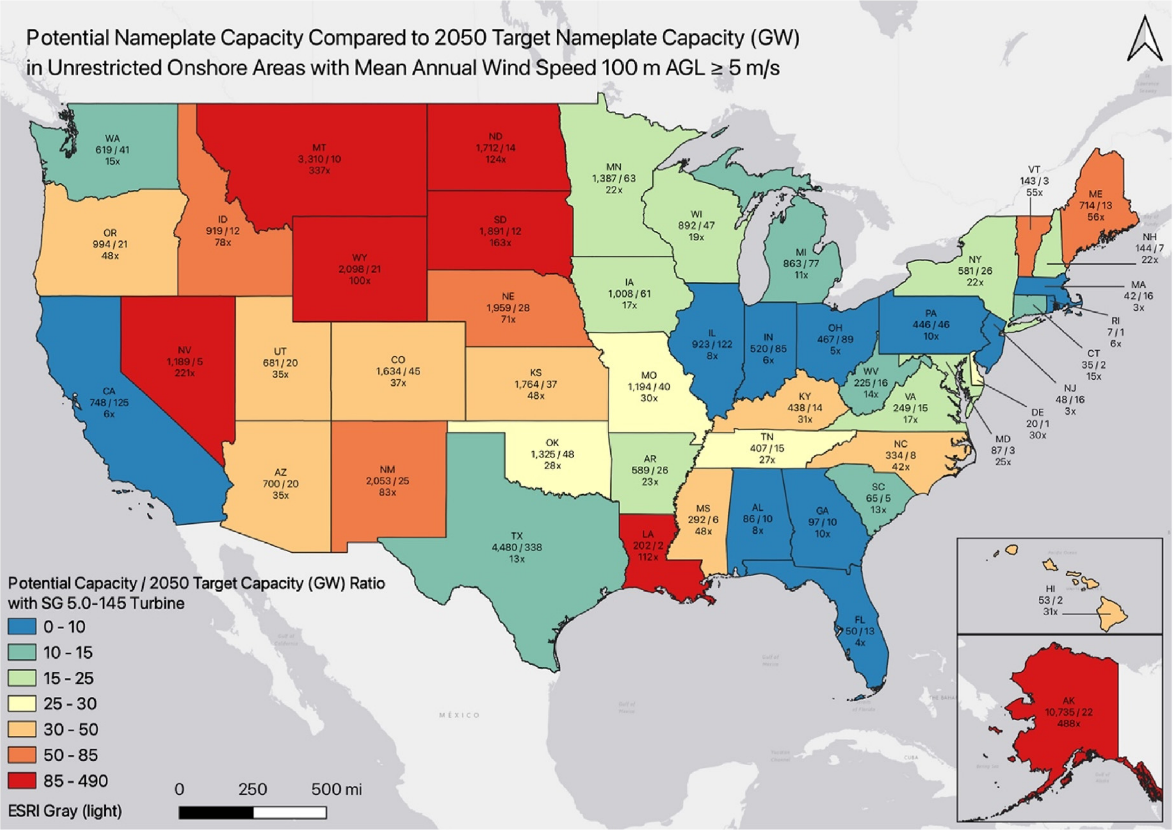

Fig. 6. Potential Nameplate Capacity Compared to 2050 Target Nameplate Capacity (GW). Potential nameplate capacity (GW) that can be realized if SG 5.0-145 turbines are installed in all available land area, calculated using Equation S2 and accounting for all restrictions and an annual mean wind speed threshold of 5 m/s at 100 m above ground level, compared with 2050 onshore wind target nameplate capacity [65]. These restrictions include buildings, major roads, minor roads, railways, navigable waterways, non-navigable waterways, water, land-use, and existing wind turbines (see Table 1 for details about each restriction layer). The ratio refers to the factor by which potential nameplate capacity can over-supply 2050 targets. Additional maps for this calculation can be found in the supplemental information (Figures S4.1-S4.12, Table S3 for potential nameplate capacities).

states throughout the central part of the country, and even as far east as New Hampshire, have higher than average capabilities of capturing wind power.

Fig. 9 shows how much wind can be captured per unit area on a more granular level than the preceding state-level maps. As before, we see similar trends in that the highest energy output regions tend to be the mid- and mid-western regions and the lowest in the southeast, but this depiction allows for more in-depth insights. For instance, we see precisely which counties could potentially contribute the highest energy output in a future heavily powered by wind, and therefore where siting efforts should be focused. The counties with the best resources and most available land have potential annual energy outputs greater than 30 GWh/km^2, and as high as 55 GWh/km^2.

The finding that is supported throughout is that each U.S. state has enough land area to meet, and usually exceed, wind energy targets. Results from this study will inform wind farm developers, city planners, energy planners, policymakers, research scientists, utilities, and the general public. This will help countries, states, cities, and energy planners make more informed decisions regarding the numbers, locations, and physical sizes of wind farms needed for wind to supply a substantial portion of the country or state's all-purpose end-use power demand (electricity, transportation, buildings, and industry). It also elucidates how much power can be generated through onshore wind resources by revealing county and state potentials, and therefore informs policy and highlights any supply gaps that exist and might require investment in alternative energy resources [45].

4. Discussion

Overall, the U.S. has far greater land area in non-exclusion zones for onshore wind energy than previously suggested. Prior estimates of the U.S. onshore potential were obtained by Lu et al., who found a technical energy production of 74,000 TWh [67]. Lopez et al. calculated an output potential of 32,700 TWh based on an installed nameplate capacity of 11,000 GW, indicating a mean capacity factor of 34% [68]. In comparison, this study estimates a potential output of 199,000 TWh based on 68,000 GW installed capacity with a mean capacity factor of 32.5% across the U.S. for the SG 5.0–145 turbine with no wind speed restriction. This study's estimate is approximately 2.7 times larger than that found by Lu et al. and 6 times larger than that from Lopez et al.

There are several notable differences that account for this discrepancy. First, Lopez et al. applies a uniform 3 km distance from all exclusions, whereas this study considers each restriction individually and follows industry standards when making buffer distance determinations. Second, land with a slope greater than 20% is excluded, while this study makes the case that these areas are not technically unfeasible, but would require a higher level of investment to develop. Furthermore, this study employs higher resolution datasets, wind resource estimates at higher hub heights to set wind speed cutoffs, and competition among turbines for limited kinetic energy. The use of a wind turbine that represents the industry standard in a future U.S. scenario is also likely a contributing factor to the larger potential found in this study as opposed to the older technology and data employed in Lopez et al. For example,

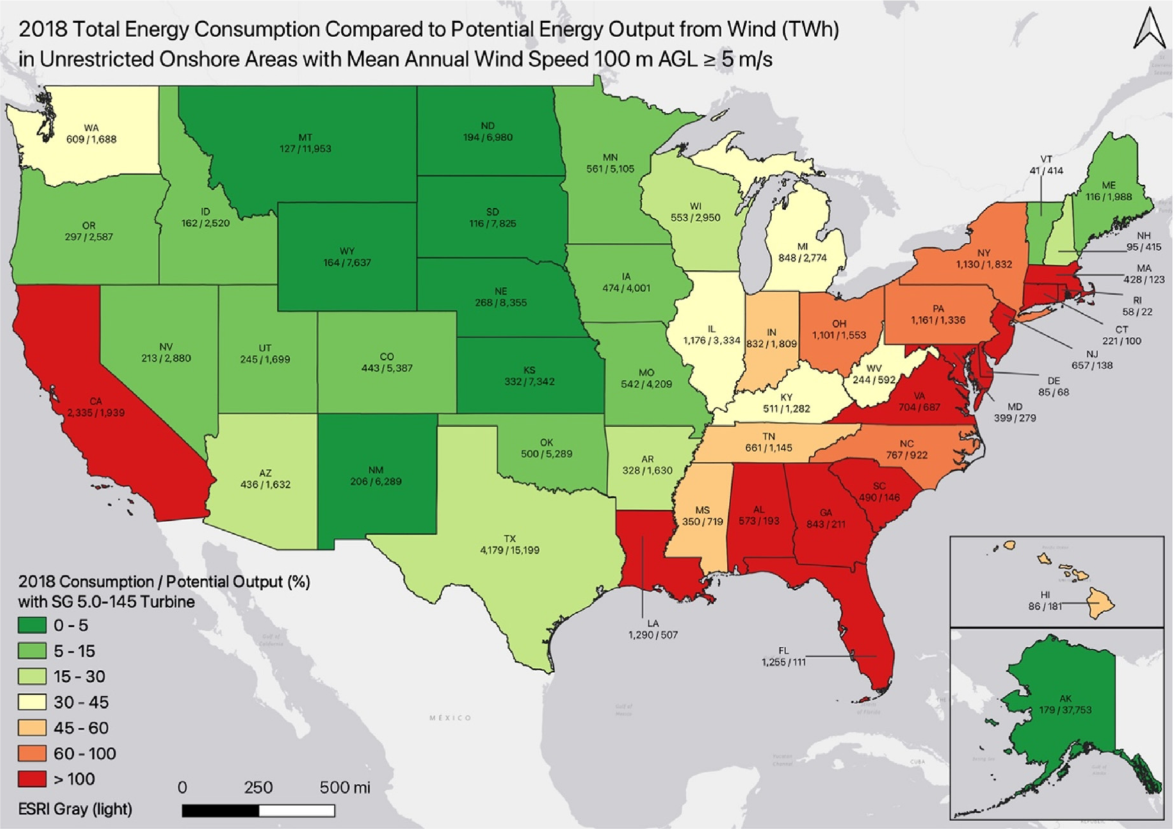

Fig. 7. 2018 Total Energy Consumption Compared to Potential Energy Output from Wind (TWh). Total energy consumption by state [66] in 2018 compared with potential energy output from wind (TWh) that can be realized if SG 5.0–145 turbines are installed in all available land area. Potential energy output is calculated using Equation S2 to find potential installed nameplate capacity, multiplied by the appropriate capacity factor (see Table S4 for capacity factors under different scenarios). This value accounts for all restrictions including an annual mean wind speed threshold of 5 m/s at 100 m above ground level (see Table 1 for details about each restriction layer). The color gradient is based on the percentage of 2018 total energy consumption (residential, commercial, industrial, and transportation) relative to the amount of energy that could be produced by wind in each state. The lowest percentages denote that potential energy production far exceeds energy expenditure. See Table S5 and Figures S5.1–S5.9 for additional maps of potential energy output and state-wise values. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Lopez et al. found that 380,306 km^2 of land area remain available in Texas with an estimated annual potential of 5,552 TWh. By contrast, this study finds that 419,877 km^2 remain available in Texas and potentially yields 17,528 TWh. Finally, perhaps the largest contributor to the increased estimate for potential output and installed capacity is the use of a higher and more realistic spacing density. As explained in Enevoldsen and Jacobson, installed and output power densities have been historically underestimated due to the inclusion of space outside of wind farm boundaries, space between clusters of turbines, and double counting. The implication of using less land area is the potential for more wind projects overall and the reduction in cost from land acquisition for a particular wind farm [14].

4.1. Expected improvements

Transitioning the U.S. to 100% clean, renewable energy has enormous benefits, and as this study shows, it is technically possible to meet or exceed energy demand in 2050 with wind energy alone. Although there are numerous paths to reaching a decarbonized economy and this study focuses on the potential of wind energy in isolation, studies show that a complete transition to a combination of wind, water, and solar resources will result in a grid that is stable 100% of the time due in part to the complementary nature of wind and solar energy [2,65]. One study finds that transitioning all energy in the U.S. might create 4.7 million more long-term, full-time jobs than lost, save 53,200 lives from air pollution per year in 2050, reduce the U.S.'s 2050 annual energy costs by 63%, and reduce annual energy, health, plus climate costs by 87% [69].

Some states and regions of the U.S. currently have very few wind energy resources, but could see tremendous benefits from installing wind turbines. In particular, most southeastern states are far behind in their progress toward meeting required renewable energy levels to meet 2050 goals. For example, Mississippi, which currently has zero wind turbines, has the potential to produce twice its 2018 total energy consumption when considering SG 5.0–145 turbines with a 5 m/s wind speed threshold. It also has 48 times more potential nameplate capacity than it needs to reach 2050 wind targets. If this state were to implement plans to reach 100% clean, renewable energy, of which onshore wind makes up 10.14%, 400 lives might be saved from air pollution in 2050, 84 million tonnes-CO_2e per year can be eliminated, energy costs can decrease by 56%, annual energy, health, plus climate costs can be reduced by 84%, and 162,000 more full-time jobs could be generated than lost, with 852 new construction jobs and 1,313 new operation jobs coming directly from onshore wind [2,69].

By providing information about wind potential, sensitive and protected areas, and other relevant restrictions, wind developers will be able to limit the initial site selection process dramatically through a more strategic selection and verification of areas for resource review studies. This is especially true of developers who

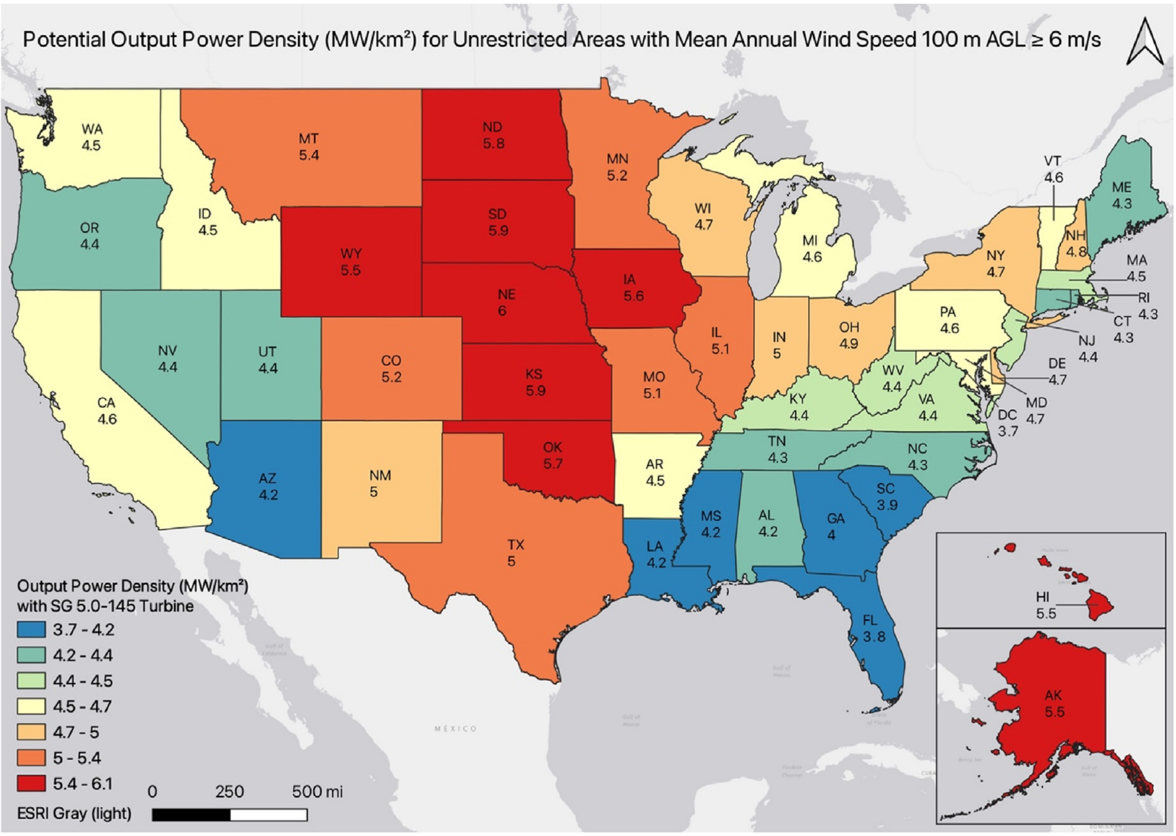

Fig. 8. Potential Output Power Density (MW/km^2). Potential output power density (MW/km^2) that can be realized if SG 5.0–145 turbines are installed in all available land area, calculated using Equation S2 and appropriate capacity factor (see Table S4 for capacity factors under different scenarios), divided by remaining land area for each state after accounting for all restrictions including annual mean wind speed threshold of 6 m/s at 100 m above ground level (see Table 1 for details about each restriction layer). The color gradient represents the output power density in each state. See Table S8 and Figures S7.1–S7.21 for additional maps and state-wise values. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

plan to build in a new area and are not necessarily familiar with the landscape, local policies, and limitations [31]. Providing more certainty at an early stage will also allow for earlier turbine selection and customer engagement, reducing the number of abandoned projects, improving investment decisions, and lowering project costs and the levelized cost of energy (LCOE) of wind.

This research aims to serve as a tool for communication. It provides developers and stakeholders with a country-wide atlas that has an unprecedented level of detail. This could help wind developers with long-range vision site selection, policymakers with setting realistic targets and providing appropriate incentives, and scientists with further feasibility assessments.

4.2. Limitations and uncertainties

Sources of uncertainty include our proposed values of buffer distances, the accuracy of the various datasets used, the extent to which buffer distances are generalizable on a national level, and the rate at which these datasets change over time.

Buffers are often defined in different ways, and can vary based on various parameters, such as proximity to sensitive infrastructure, urban areas, or federal land used for defense-related work. In some cases, ordinances date over a decade, in which time both wind turbine technology and possibly attitudes toward wind have changed considerably. Moreover, it is assumed that these policies are not fixed, but rather have the potential to change in the near future as wind technology might become more accepted.

Furthermore, private land is included in viable development area. Any land not captured by the restrictions above is included in the leftover land area available for development. The reasoning is based on the notion that this land is technically unrestricted, and landowners might choose to lease the land at a certain compensation level, so it should not be excluded. The model also does not take into account social willingness or sensitivity to financial incentives, but instead aims to inform both.

The objective of this atlas is not to instruct developers on precisely where to install upcoming projects, but rather to quantify the potential across the U.S. Further analysis is necessary at the local scale to account for county-level laws, sensitive ecosystems particular to that area, and regulatory issues.

Additionally, no determinations are made regarding a cost threshold, as investors must decide what size wind farm is appropriate for their region of interest. Due to the high diversity of wind profiles and corresponding profitability of wind farms in different regions, one specific wind speed threshold for economic viability is also not prescribed. It is likely that as wind turbines continue to evolve, even higher wind potentials can be achieved. Similarly, the design of a wind farm is not stipulated. Of course, not all the available land for wind development will be used for that purpose, but there is still an inherent tradeoff between turbine density and power output, which has not been explored in this study. The choice of setback requirements will influence the degree to which continued deployment of wind energy interfaces with socially-driven saturation considerations.

Another important component for planning is the wind energy supply chain. Because distance to transmission lines and the corresponding costs to interconnection with the grid can be hinderances to building wind farms, it is important to consider the

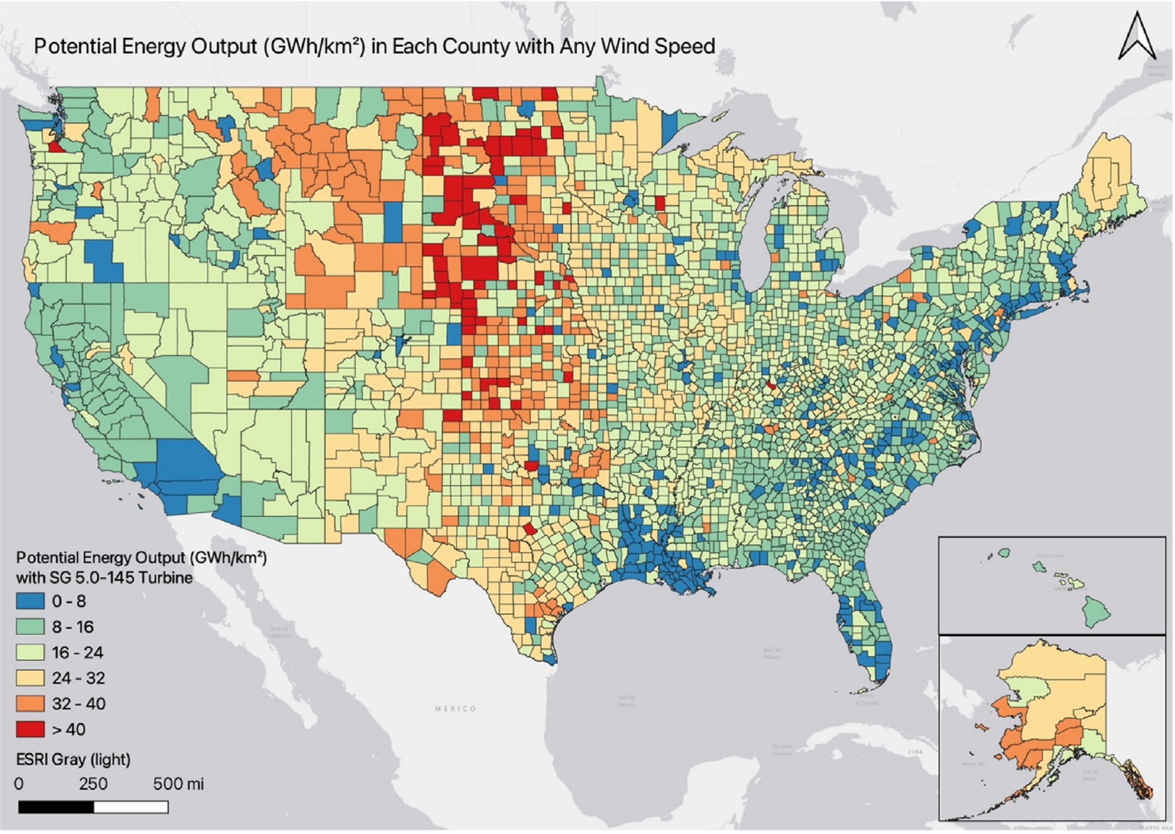

Fig. 9. Potential Output Energy Density (GWh/km^2) in Each County. Potential energy output (GWh/km^2) in each U.S. county, normalized by county area, if SG 5.0-145 turbines are installed in all available land area after accounting for every restriction except wind speed (see Table 1 for details about each restriction layer). Potential energy output is calculated using Equation S2 to find potential installed nameplate capacity, multiplied by the appropriate capacity factor (see Table S4 for capacity factors under different scenarios), divided by total county area. The color gradient represents the potential energy output in each U.S. county. These values are calculated before array losses are accounted for. See Figures S8.1–S8.9 for additional maps.

transmission and substation network, for instance [70]. In contrast to the restrictions described above, proximity to necessary logistical infrastructure, such as existing transmission, should be seen as an opportunity to reduce costs of new projects.

4.3. Conclusions

This paper provides a wind atlas of the United States that is subject to geographical, infrastructural, technical, and meteorological constraints, and accounts roughly for competition among turbines. Using GIS-based maps, we develop a detailed atlas that accounts for exclusions, such as wind resources, restrictions (including environmental and technical characteristics that can impede wind projects), regulations (including distance requirements to infrastructure, buildings, military land, and protected areas), and wind turbine information (dimensions, footprint, and energy output of modern wind turbines). We present the resulting aggregated data on county, state, and country levels to complement the 10 m resolution atlas. Overall, 27% (2,539,000 km^2) of land area is available for wind farm development in locations with mean wind speeds of 6 m/s or higher after taking into account all infrastructural restrictions, but with no array losses. This translates to ~32 TW of potential nameplate capacity, which is more than enough to power each state with wind's share of a 100% clean, renewable energy system for all energy purposes in 2050. In addition to finding the maximum available land area for wind energy development at different wind speed thresholds, we also estimate the maximum possible number of wind turbines, nameplate capacities (GW), energy outputs (TWh) with and without array losses, nameplate capacities compared with population (people per MW), output power densities (MW/km^2), output energy densities (TWh/km^2), and capacity factors for several turbine scenarios and wind speed thresholds for every state, and in some cases, county. The results here can be used to expedite the wind farm siting process, reduce investment risk, decrease future project LCOE, and increase access to relevant data for wind farm developers—ultimately creating jobs, saving water resources, generating revenue for local communities, and reducing air pollution and carbon emissions, bringing us closer to a sustainable energy system [71].

Data availabilty

All datasets used in this study are publicly available and can be found by accessing the referenced studies, except for SG power curves, which can be provided by SGRE upon request. Further information and requests for resources should be directed to the lead contact, Anna-Katharina von Krauland (krauland@stanford.edu).

Authorship contribution statement

Anna-Katharina von Krauland: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Writing—Original Draft, Writing—Review, and Editing, Visualization, Project Administration, Funding Acquisition. **Finn-Hendrik Permien:** Methodology, Writing—Review, and Editing. **Peter**

Enevoldsen: Conceptualization, Methodology, Writing–Review, and Editing, Supervision. **Mark Z. Jacobson:** Conceptualization, Writing–Review, and Editing, Supervision, Funding Acquisition.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2021.100046.

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