Dynamic land use implications of rapidly expanding and evolving wind power deployment

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Abstract

The expansion of wind power poses distinct and varied geographic challenges to a sustainable energy transition. However, current knowledge of its land use impacts and synergies is limited by reliance on static characterizations that overlook the role of turbine technology and plant design in mediating interactions with the environment. Here, we investigate how wind technology development and innovation have shaped landscape interactions with social and ecological systems within the United States and contribute to evolving land area requirements. This work assesses trends in key land use facets of wind power using a holistic set of metrics to establish an evidence base that researchers, technology designers, land use managers, and policymakers can use in envisioning how future wind-intensive energy systems may be jointly optimized for clean energy, social, and environmental objectives. Since 2000, we find dynamic land occupancy patterns and regional trends that are driven by advancing technology and geographic factors. Though most historical U.S. wind deployment has been confined to the temperate grassland biome in the nation’s interior, regional expansion has implicated diverse land use and cover types. A large percentage of the typical wind plant footprint (∼96% to > 99%) is not directly impacted by permanent physical infrastructure, allowing for multiple uses in the spaces between turbines. Surprisingly, turbines are commonly close to built structures. Moreover, rangeland and cropland have supported 93.4% of deployment, highlighting potential synergies with agricultural lands. Despite broadly decreasing capacity densities, offsetting technology improvements have stabilized power densities. Land use intensity, defined as the ratio of direct land usage to lifetime power generation of wind facilities, has also trended downwards. Although continued deployment on disturbed lands, and in close proximity to existing wind facilities and other infrastructure, could minimize the extent of impacts, ambitious decarbonization trajectories may predispose particular biomes to cumulative effects and risks from regional wind power saturation. Increased land-use and sustainability feedback in technology and plant design will be critical to sustainable management of wind power.

1. Introduction

Pathways for clean energy transition increasingly harness wind power as an affordable source of energy (Brown and Botterud 2020). In the United States, recent deep decarbonization scenarios highlight the possibilities of tapping into a transformative growth potential for wind power that could entail order of magnitude increases in projected capacity (Larson et al 2020). Although clean energy objectives would stand to benefit under such high contributions of wind power, it is unclear how its expansion could affect other key sustainability objectives (United Nations (UN) 2015).
Understanding the varied sustainability challenges and opportunities presented by wind power requires deeper insight into how the technology is deployed. This information is critically needed because the distributed nature of wind power creates broad interfaces with the environment that drive diverse landscape interactions (Pasqualetti 2000, Fargione et al 2012, Zaunbrecher et al 2018, Hayes et al 2019). Because trade-offs and opportunities for wind power depend on location, the geographic context for its deployment is a critical facet of wind power sustainability. Surprisingly, despite increasing awareness of near-term technical and economic viability of high wind power contributions (Mai et al 2012, International Energy Agency (IEA) 2018) and social acceptance issues (Wolsink 2000, Rand and Hoen 2017), investigations into the spaces and places underpinning the energy transition (Bridge et al 2013) remain limited. As a result, key uncertainties persist regarding geographic characteristics of wind power deployment, its integration into the environment and practical implications for future energy systems.

In this research, we illuminate the emerging interface between wind energy deployment and accompanying social and ecological communities using empirical analysis to discern the dynamic nature of its space use and occupancy patterns during the past two decades. We focus on areal impacts and their trends because they represent core themes in the geography of energy development (Copeland et al 2011) and are amenable to spatial inference. Findings on capacity density, power density and land-use intensity metrics are complemented with detailed investigations of land use, land cover, and structure proximity trends across time to present an overarching perspective of wind power land use within the United States. We extend prior work in critical ways, linking observed changes in land area requirements to technology trends and innovation, as well as exposing the extent of spatial interfaces between wind power and the built and natural environment. In doing so, we uncover the shifting character of wind power deployment and highlight potential challenges from continued growth as well as emerging technology solutions.

1.1. Metrics for land area requirements

Land requirements of wind power are often seen as a constraint to future broad scale deployment. This perception is based on the conventional wisdom that wind plants typically require larger land areas per megawatt (MW) of capacity than solar technologies and fossil fuel-based sources (Smil 2008, Jordaan et al 2017, van Zalk and Behrens 2018). Such generalizations can be controversial, however, because they hinge on key assumptions including how occupied or impacted lands are defined and which aspects of the life cycle of energy projects are included in the footprint (Lovins 2011). Compared with other forms of energy, the specific impact of wind power on the landscape is distinct and highly nuanced. Much of its uniqueness arises from the distributed nature of wind turbines, even in plants that are hundreds of megawatts, that generally confines direct impacts within concentrated areas around the pad and roads but span large areas due to required spacing (Enevoldsen and Jacobson 2021). For instance, a large percentage of the typical wind plant footprint (~96% to >99%) is not directly impacted by permanent physical infrastructure (Diffendorfer et al 2019), allowing for multiple uses in the spaces between turbines.

Numerous metrics have been proposed to quantify the extent of wind power facilities and their attendant implications though no single definitive metric has emerged that broadly captures the multifaceted nature of its land usage and impacts. Investigations into the elusive wind power footprint have established land area requirements as the primary measure of wind power’s land usage. Capacity density, CD, is a leading metric for evaluating land area requirements. In theory, it is a simply defined metric that describes the amount of land area that is needed to support a megawatt of installed capacity. It is computed as follows:

\[ CD = \frac{C}{A}, \]

where \( C \) is the installed capacity in megawatts and \( A \) is the land area in square kilometers. Its units are MW km\(^{-2}\). Typically, the land area quantity, \( A \), that is used to inform capacity density is inclusive of all lands contained within the outermost bounds of a wind plant, which we refer to throughout this paper as the ‘footprint.’ The reason for this is that spacing between turbines is a critical engineering feature of the wind plant. Enforcing sufficient spacing between rows of turbines fosters energy production by minimizing detrimental wakes to downwind turbines whose impacts are greatest at short distances and can impose significant losses throughout the turbine array. Thus, even though the interstitial spaces between turbines may not be directly impacted by turbines or associated infrastructure, this land area is generally necessary to support wind energy production.

Critical aspects of wind power technology and its performance tend to be neglected in discussions that rely exclusively on conventional land area requirement metrics such as capacity density. While capacity density quantifies land area requirements in relation to installed capacity, it does not account for either the average power or total quantity of energy generated over the footprint area. This is an important qualifier because energy production can vary substantially based on factors that include the quality of the wind resource, turbine technology, plant operations and the plant layout. Unlike capacity density, which measures rated power per unit area, the power density, PD, and energy density, ED, metrics account for realized
levels of plant performance. Power density is calculated as follows:

\[ PD = \frac{C \cdot cf}{A} \]  

(2)

where \( cf \) is the capacity factor and \( A \) is as defined for capacity density. The numerator represents the discounted nameplate capacity equivalent to the average power. The units of capacity density are MWe km\(^{-2}\), where MWe is average megawatts.

The energy density metric represents total energy production, measured in terms of megawatt-hours (MWh), over a given period per unit land area. It is calculated using the following equation:

\[ ED = \frac{C \cdot cf \cdot H}{A} \]  

(3)

where \( H \) is hours (nominally 8766, representing annual power generation in an average year). The units for energy density are MWh/km\(^2\).

Insights provided by power density and energy density metrics are complementary to those yielded by capacity density and can inform how wind plants evolve in their land usage and productivity. Note that because power density and energy density convey similar information, we choose to focus on the former.

A persistent question that arises when evaluating environmental tradeoffs of different energy sources is how they compare in terms of energy produced per unit area. Standardization of land impacts and power generation is needed to place different technologies on a level playing field. While the power density and energy density metrics can inform trends in wind power productivity, they do not allow for robust comparisons with other technologies whose life cycles or fuel production cycles differ substantially from renewables, nor do they acknowledge the variability in the extent of impact, for example, between a wind plant and a nuclear power plant. Moreover, once installed, renewables can continue to generate electricity on the same plot of land for an extended period without exhausting the resource. Acknowledging these inherent difficulties, the land use intensity metric, LUI, leverages the concept of directly impacted area to describe direct land usage relative to lifetime energy generation (Wachs and Engel 2021). Land use intensity is computed as follows:

\[ LUI = \frac{A_D}{C \cdot cf \cdot H \cdot y} \]  

(4)

where \( A_D \) is directly impacted area (m\(^2\)), \( H \) is the hours in an average year (8766) and \( y \) is the assumed generating lifetime of a wind turbine in years. As described earlier, \( A_D \) is typically only a small percentage of \( A \) for wind power facilities. The units for land use intensity are m\(^2\)/GWh.

Studies on capacity density, power density, energy density and land use intensity metrics have characterized different aspects of land area requirements of wind power while generally revealing large uncertainties. Although information on basic land requirements is essential to wind power planning and analysis, a holistic view of the sustainability of wind power deployment would be supported by deeper awareness of interactions with social and ecological variables and would further capture the non-consumptive nature of wind power deployment made possible by its integration into the landscape (Harrison-Atlas et al 2021). For example, because not all lands within the outermost extent of a wind plant (i.e. the footprint) are directly affected by plant infrastructure or operations, multiple land uses are practical in these settings. To acknowledge these complexities is to apply discretion when interpreting any single metric describing the land usage of wind power. Indeed, as interest from the research community converges towards balanced evaluation of energy systems, more comprehensive and nuanced assessments of wind power deployment are needed to cultivate actionable knowledge for sustainable management and planning purposes.

1.2. Literature review

To date, studies of land use for wind power have largely characterized it as a static phenomenon. In an influential early work, Denholm et al (2009) conducted an empirical assessment of installed wind power, focusing on the U.S. fleet with an analysis that established an important benchmark of approximately 3 MW km\(^{-2}\) for land use requirements. Numerous studies have conducted meta-analyses of land requirements (e.g. van Zalk and Behrens 2018, Enevoldsen and Jacobson 2021, Wachs and Engel 2021). Their results remain highly variable and are sensitive to methods for quantifying plant boundaries and total impacted land area. In other cases, static land requirement metrics have been used to project future habitat impacts (McDonald et al 2009), assess the cumulative footprint of future energy development (Copeland et al 2011), identify low-impact development pathways (Kieseker et al 2011), evaluate energy sprawl (Trainor et al 2016) and examine spatial land use tradeoffs (Wu et al 2020). Static approaches have also been used to illuminate the interplay between land use constraints and wind potential under renewable energy scenarios (Rinne et al 2018, Lopez et al 2021, Mai et al 2021). Determining land eligibility for wind power remains an important and active area of research (Ryberg et al 2018, McKenna et al 2022). Where others have examined deployment through time, the focus has typically been limited to land requirements. For instance, Miller and Keith (2018) investigated land footprints of renewables, comparing capacity densities among wind and solar facilities in the United States and...
documenting trends in required land area. Building on this past body of work, deeper analysis of land occupancy patterns and linkages to technology advancements remains necessary to evaluate both drivers of and interactions with evolving wind energy deployment.

At broad geographic scales, few studies have examined landscape impacts beyond total footprint or area requirements. For a region in Denmark, Möller (2010) analyzed spatial interactions of wind power with populations using metrics describing trends in visibility, proximity, and turbine density. Focusing on historical wind development in Germany, Bunzel et al. (2019) investigated linkages between land use policies and geographic development patterns. Nitsch et al. (2019) compiled site characteristics of wind plants in Austria and Denmark to gauge land availability for future deployment from an operational perspective. Deeper assessments of social and ecological impacts are conventionally performed at the site level (e.g. Johnson et al. 2003, Kunz et al. 2007, Wang and Wang 2015) including some instances where land transformation was quantified for a limited number of facilities (e.g. Jones and Pejchar 2013, Wolaver et al. 2018, Diffendorfer et al. 2019, Xu et al. 2019). Although rare, broad scale studies have revealed the extent of ecological impacts that can arise under wind power expansion when renewable energy and conservation planning are siloed. For example, Rehbein et al. (2020) conducted a global assessment of major forms of renewable energy development on important areas for biodiversity conservation and found significant overlap. Without more integrated knowledge about potential impacts and coordination around joint energy and conservation planning, they concluded that a singular focus on energy expansion could undermine progress towards sustainability goals. Recently, Turkovska et al. (2021) analyzed land cover change for Brazilian wind power installations, reporting variable impacts across land use regimes while highlighting the environmental challenges that occur when regional expansion proceeds disproportionately on ecologically sensitive lands.

Collectively, these efforts have established a foundational understanding of wind power deployment. Nevertheless, critical knowledge gaps exist around fleet-level and regional deployment characteristics as well as the effects of changing technology on emerging trends. Unfortunately, these gaps limit current abilities to characterize and anticipate the consequences of rapidly expanding and evolving technology. Given parallel interests in substantive ecological and social objectives, studies that account for the nuances and complexities of wind power land use are increasingly needed to plan for and effectively manage an expanding wind energy portfolio (MacDonald et al. 2016, Ioannidis and Koutsoyiannis 2020, Wu et al. 2020). These efforts are especially critical as energy planners explore scenarios with ever increasing penetrations of wind power in the electricity sector (Veers et al. 2019, Cole et al. 2020, Larson et al. 2020, Mai et al. 2021) and electrification grows as an important broader trend in energy. Cultivation of deeper understanding of potential land use impacts (e.g. on ecological habitats) and synergies (e.g. applying novel turbine control strategies and plant designs to mitigate potential impacts on sensitive habitat) in support of policy and environmental planning will be enabled by evaluations that capably reflect the complexity and evolution of real-world deployments (figure 1).

1.3. Contributions

In this work, critical findings on the regional clustering of wind plant deployment and turbine proximity to existing building structures are presented. In addition, we examine how regional deployment has shifted land occupancy patterns and contributed to national trends in the aggregate. Increasing land area requirements (i.e. capacity densities) are driven by changing technology though concurrent performance gains have stabilized power densities, with land use intensities trending downwards. We use these results to guide discussion around potential barriers to and solutions for emerging electricity systems that rely on very large quantities of wind power. Although the cumulative footprint of wind energy (46.915 km$^2$) is equivalent to the combined land area of New Hampshire and Vermont, deployments are largely found in agricultural settings and within close proximity to the built environment including other wind power facilities. Geographic expansion projected under a deep decarbonization scenario could predispose multiple biomes to landscape effects of transformative growth though the extent of directly impacted lands is small relative to the total footprint. There remains further potential for technological solutions to mitigate interactions with social and ecological communities. At the same time, advances in technology, both for turbines and plant design, provide engineers, policymakers, and land use managers with additional levers by which they can alter the character and extent of land use impacts.

Overall, our findings support conceptual advancements in understanding the role of changing technology and deployment practices in determining essential land use characteristics of wind power. These insights reveal a more varied and novel land use component of wind power than is typically represented in the literature and highlight opportunities for technology-based mitigation of land use impacts. Land managers and decision makers may draw on the presented evidence to more precisely characterize implications of existing and future deployment. Although significant questions remain, deeper awareness of the relevant complexities surrounding wind power land use enabled by the resolution and scope of
the research presented here will be increasingly valuable for managing progress towards decarbonization and sustainability goals.

2. Results

We define contemporary wind plants as those built after 2000 and having a minimum installed capacity of 2 MW. Our analysis is based on the October 2020 database of installations and includes operating wind plants installed in 2020 (representing 3972 MW of installed capacity). Our sample includes 1089 wind plants accounting for 106,697 MW of installed capacity and represents 98.7% of total installed capacity captured by the U.S. Wind Turbine Database (USWTDB) at the time of this release (Hoen et al 2018). Wind plant deployment varies regionally, with plants in our sample present in 40 states (figure 1). In the following section, we refer to geographic units based on U.S. Census regions but adapted to cover equal areas for the sake of facilitating geographic comparisons (Lopez et al 2021).

2.1. Clustering of wind power installations at local to regional scales

Across the nation, wind power deployment is geographically variable yet concentrated at multiple scales. At the regional scale, current deployment is heavily skewed towards the South Central \( (n = 266, \text{MW} = 37,192) \) and Great Plains \( (n = 315, \text{MW} = 29,722) \) regions that span the wind belt. Considerable development has also occurred in the Great Lakes \( (n = 121, \text{MW} = 11,877) \), Pacific \( (n = 134, \text{MW} = 11,570) \), Mountain \( (n = 92, \text{MW} = 7,547) \), and Northeast \( (n = 112, \text{MW} = 4,682) \) regions. In comparison, the Southwest \( (n = 31, \text{MW} = 2,757) \) and Southeast regions \( (n = 18, \text{MW} = 1,348) \) remain less developed. At more local scales, clustering of wind plants is commonly observed. These local and regional clustering trends could portend emerging...
challenges for wind power expansion, particularly as upwind plants have the potential to induce a competitive disadvantage on neighboring downwind plants by impairing wind resources in ways that affect profits (Lundquist et al 2019). We find high potential for such interactions with 80% of wind plants nationwide occurring within 11 km of another wind power facility.

2.2. Growth of wind plant sizes

Nationwide, we find a mean installed capacity of 97.9 MW, with an average of 51 turbines per wind project. Turbine counts vary substantially, ranging from 1 to 293 turbines per project. Regional differences in plant size are considerable—for example, there is a greater than threefold difference in mean project capacity between South Central (139.8 MW) and Northeast (41.8 MW) regions. Trends in increasing plant capacities are observed for all regions with a majority of recent capacity additions being driven by plants exceeding 150 MW (see SI available online at stacks.iop.org/ERL/17/044064/mmedia). Nationally, plant sizes have grown by 1435% since 2000 with median installed capacities increasing from 11.7 to 179.9 MW.

2.3. Technology and deployment drivers behind increased land area requirements

Dynamic effects of rapid deployment and technology change over the past two decades challenge the applicability of static views on wind power, particularly for informing key aspects related to its evolving land usage. We measure the total area of each wind plant using a uniformly applicable method that relies solely on turbine locations to derive the boundaries of its geographic footprint (see section 4). These area estimates reflect operational requirements of wind plants, which are predominantly non-consumptive and make no determination as to the level of impact experienced by the occupied lands. We estimate capacity density for each wind plant by standardizing its installed capacity (MW) against its footprint area (km²). Building on this concept, we integrate information on historical plant performance to meaningfully characterize power production efficiencies on a per-area basis using the power density metric.

Across all years of our analysis, we find a national average capacity density of 4.3 MW km⁻² but with substantial variation among plants (SD = 3.5 MW km⁻²). However, since 2000, growth of wind plant area has outpaced increases in project capacity. Footprints increased by 4477.5% during this period, with the median wind plant area increasing from 1.9 to 84.8 km². Accordingly, as wind plants have increased in gross size, yearly national average capacity densities have decreased since 2000, dropping 68%, from 7.0 to 2.2 MW km⁻². A focus on national trends, however, belies important regional variation in capacity density (figure 2). Capacity densities are lowest on average for the Great Lakes (3.1 MW km⁻²), Great Plains (3.2 MW km⁻²), and South Central (3.3 MW km⁻²) regions, followed by the Southwest (4.2 MW km⁻²) and Mountain (4.4 MW km⁻²) regions. Higher densities were observed in the Northeast (6.5 MW km⁻²), Pacific (6.9 MW km⁻²), and Southeast (7.6 MW km⁻²) regions.

Since 2010, deployment has largely been concentrated in South Central, Great Plains, and Great Lakes regions (see Supplemental Information), contributing to the overall national decline in this key metric. Lower capacity densities are typical of these regions and can be explained through various social and physical aspects of the environment that affect the process of wind site development (Diffendorfer and Compton 2014). For example, recent analysis has shown that geographic variation in capacity density is driven by characteristics of the local wind resource, urban accessibility, forest cover, fragmentation of lands suitable for wind development and terrain (Harrison-Atlas et al 2021). To the extent that these spatial drivers continue to shape future turbine installation practices, it is likely that observed regional differences in attainable capacity densities will persist. However, technological advancements are also altering plant capacity densities alongside regional deployment patterns as discussed in more detail in the following section. Evidence of these technology-driven trends can be seen through net regional declines in capacity density that have occurred between 2000 to 2020 in several regions of the country.

2.4. Performance gains stabilize power densities, offsetting regional declines in capacity density

A concurrent trend (with declining capacity density) has been a decrease in the specific power (i.e. ratio of nameplate capacity to rotor swept area) of turbines (figure 2). This trend has occurred as increases in rotor diameter have outpaced fleet-wide increases in generator capacity (Wiser et al 2020a). All else equal, a transition toward lower specific power is expected to result in greater land requirements (i.e. lower capacity densities). This occurs because increased turbine spacing becomes necessary to mitigate potential energy losses to downstream turbines that could otherwise result from pronounced wake effects driven by large rotors. Accounting for temporal trends, we find that observed annual variation in capacity density is explained by changes in specific power and capacity (capacity density ∼0.06 × specific power −0.03 × capacity +0.55). We include capacity as an additional explanatory term to account for its
Figure 2. Regional (A) and national (B) trends in wind plant capacity density (MW km$^{-2}$) and average power density (MWe km$^{-2}$) for projects greater than 2 MW deployed between 2000 and 2020. Results in A are presented as capacity-weighted averages for plants in multiyear increments (2000–2004, 2005–2008, 2009–2012, 2013–2015, 2016–2017, 2018–2020). The power density metric accounts for plant performance on a per-footprint basis using a modeled capacity factor (Wiser et al. 2020a).

Broadly observed regional decreases in capacity density have contributed to a decrease in national average capacity density during the past two decades. This trend has been precipitated by marked reductions in specific power (B). Higher capacity density plants typically yield higher power densities (C) though, as observed consistently among all regions, plants with lower capacity densities tend toward greater capacity factors (D). Note that a total of 20 plants exceeding the displayed capacity density and power density limits are not shown.

potentially confounding relationship with both specific power and capacity density. The regression is statistically significant ($R^2 = 0.7$, $F(2,17)$, $P < .001$). Moreover, as detailed in figure 2, decreases in capacity density have been offset by capacity factor improvements in plants built after 2013. These performance gains have largely yielded steady to increasing power densities at the regional and national scale. Between 2005 and 2017, the average national power density was 1.02 MWe km$^{-2}$, with a low of 0.76 MWe km$^{-2}$ in 2007 and a high of 1.42 MWe km$^{-2}$ in 2013.

2.5. Concentrated extent of directly impacted area drives low land use intensity of wind power

Estimates of land transformation caused by energy facilities can inform ecological impacts of various technologies but must be standardized in terms of the nature of impact. As we have presented it, the footprint is a comprehensive measure of all lands contained within the outermost bounds of the wind plant including the indirectly used spaces between turbines (Kuvesky et al. 2007). In contrast, the substantially smaller areas directly impacted or otherwise permanently occupied by physical infrastructure have been investigated using field surveys and through analysis of remote-sensing imagery. These studies have generally found that 2%–5% of the wind plant footprint

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$^4$ Information on capacity factor and power density was limited to plants built between 2005 and 2017 because of data availability.
(i.e. total area spanned) is directly impacted though recent evidence suggests that these areas may be even less extensive. Nailing down generalized insights into the extent of directly impacted areas remains difficult because these outcomes vary based on plant configuration and are also sensitive to whether temporary disturbances such as transient roads are included in the definition (Denholm et al 2009). Contemporary research conducted by Diffendorfer et al (2019) examined the direct land-use impacts of 39 wind plants across the United States. They evaluated the surface development, road networks, and turbine locations created during the construct of the wind facility. Key findings were that directly impacted lands account for a small fraction of the total footprint (generally, 1%–4%) with a mean of 1.61%, maximum of 4.3%, minimum reaching close to 0%, and standard deviation of 1.36% of the total plant area. In the cases where direct impacts reached close to 0%, the placement of wind facility equipment overlapped significant pre-construct disturbances (e.g. turbines were placed directly adjacent to an existing farm road). In terms of generalizing hectares (ha) directly impacted per megawatt, an approach that avoids having to deal with inconsistencies in how plant footprints are delineated, Diffendorfer et al found a mean direct land impact of 0.65 ha MW$^{-1}$, maximum of 2.06 ha MW$^{-1}$, minimum near 0 ha MW$^{-1}$, and standard deviation of 0.56 ha MW$^{-1}$. While Diffendorfer et al (2019) provide a rigorous update to direct land use, they do so only by capturing permanent disturbances and not temporary disturbances that would prove useful for further understanding ecological impacts.

Making the distinction between the broad-spanning nature of the wind plant footprint and the concentrated extent of directly impacted lands is critical from a sustainability perspective. Within the footprint, indirect land usage is non-consumptive, without the acute physical environmental transformations that accompany instances of directly impacted lands. The land use intensity metric leverages the concept of directly impacted area to describe direct land usage relative to lifetime power generation (assumed here to be 25 years). Nationwide, we find that the mean land use intensity of wind plants is between 13 and 168 m$^2$ GWh$^{-1}$. The range of estimated land use intensities is produced by taking the upper and lower bounds of the ratio of direct impact area to installed capacity (0.09–1.21 ha MW$^{-1}$) determined by the mean ± standard deviation of the values provided Diffendorfer et al (2019). As compared with previous findings of land use efficiencies for wind power detailed recently in a comprehensive review by Wachs and Engel (2021), our results generally reveal that wind power has a low land use intensity. Our estimates are in line with reported ranges though published estimates vary by an order of magnitude. Commensurate with our findings on increasing power densities, land use intensities have largely exhibited regional decreases since 2005 (see SI), signaling a broader trend of increased wind energy production per unit directly impacted area.

### 2.6. Characteristic land use settings for wind deployment

The distributed nature of wind power deployment and its landscape arrangement creates both opportunities and challenges for low impact integration with the environment. While it allows for multiple use opportunities, it also drives physical interactions with social and ecological systems. Here we analyze interactions of wind power with the landscape focusing on land use and land cover characteristics of the footprint. In the absence of more comprehensive data on how lands are used by people, we rely on a land use proxy primarily to inform our understanding of land occupancy. Land cover is used to characterize biophysical attributes of the interface between wind power and the environment with relevance to both social and ecological systems. More specifically, land use describes characteristics of land management and ultimately social or human interests. In some instances, these human uses are complementary to the biophysical characteristics described by land cover (Turner et al 1993). For each variable, we report the predominant type occurring within the wind plant footprint.

Wind plant deployment on public lands is limited as we find only 12 of these plants (929 MW; 1.6%) nationwide. All instances of public land occupancy occur in western states, including California, Colorado, Idaho, Montana, Nevada, Oregon, Utah, and Wyoming. We note that total deployment on public lands could conceivably be greater due to the multi-use nature of federal lands. For instance, classification of timber and park land uses could also fall under public domain depending on the ownership characteristics. At the national level, the majority of plants occur on lands used as cropland ($n = 527; 48.4\%$) and rangeland ($n = 490; 45\%;$ table 1). Collectively, these plants account for approximately 105 GW of installed capacity. Nearly half (46.7%) of rangeland plants are in Texas, California, and Oklahoma. Instances of rangeland land use found in the Northeast reflect source data ambiguities that result from the assignment of a singular classification for multi-use lands. The rangeland designation is based on ownership and management information and would likely encompass other uses such as timber and grazing that are traditionally supported under similar management regimes. Similarly, 51.4% of cropland plants are in Iowa, Minnesota, Texas, and Illinois. Plants associated with lands used primarily for residential use are relatively uncommon, occurring in 17 instances, primarily because landscapes with interspersed residential development (i.e. low density) tend to be spatially dominated by other land uses. These plants are largely confined to the
Table 1. Dominant land use and land cover composition of U.S. wind plants. Land use refers to the primary use of the land and is sourced from the National Land Use Dataset (NLUD; Theobald 2014). Land cover describes biophysical characteristics and is characterized using the National Land Cover Database (NLCD; Yang et al. 2018).

<table>
<thead>
<tr>
<th>Land use category (NLUD, Level 2)</th>
<th>Number of plants</th>
<th>Installed capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropland</td>
<td>527</td>
<td>55,664</td>
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<tr>
<td>Rangeland</td>
<td>490</td>
<td>49,146</td>
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<tr>
<td>Residential</td>
<td>17</td>
<td>102</td>
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<tr>
<td>Public</td>
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<td>929</td>
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<td>Industrial</td>
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<td>Park</td>
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<td>379</td>
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<tr>
<td>Commercial</td>
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<tr>
<td>Institutional</td>
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<td>14</td>
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<tr>
<td>Timber</td>
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<td>79</td>
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<td>General</td>
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<td>10</td>
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<tr>
<td>Natural area</td>
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<tr>
<td>Wetland</td>
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<tr>
<td>Transportation</td>
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<td>2</td>
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<tr>
<td>Private easement</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Land cover class (NLCD)</th>
<th>Number of plants</th>
<th>Installed capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultivated crops</td>
<td>550</td>
<td>58,115</td>
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<tr>
<td>Grassland/herbaceous</td>
<td>228</td>
<td>24,026</td>
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<tr>
<td>Shrub/scrub</td>
<td>153</td>
<td>17,256</td>
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<td>Deciduous forest</td>
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<td>4,229</td>
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<td>Pasture/hay</td>
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<td>1,588</td>
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<td>Evergreen forest</td>
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<td>647</td>
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<td>Barren land</td>
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<td>455</td>
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<td>Developed, medium intensity</td>
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<td>16</td>
</tr>
<tr>
<td>Developed, high intensity</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>Mixed forest</td>
<td>4</td>
<td>107</td>
</tr>
<tr>
<td>Developed, low intensity</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Emergent herbaceous wetland</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Woody wetland</td>
<td>1</td>
<td>215</td>
</tr>
</tbody>
</table>

Northeast (two exceptions are in Texas and Missouri) and tend to be smaller projects with a mean installed capacity of 6 MW. Occupation of industrial use lands is also uncommon—we find 11 plants—six commercial and five classified under institutional use. A total of 12 plants are observed in areas designated as parks\(^5\) natural areas, or easements\(^6\). Wind plant deployment on land designated for timber usage is identified in four instances.

Land use occupation of plants varies regionally—for example, rangeland is a more common land use among wind plants in western states (figure 3).

Patterns of land cover composition generally follow the major land use categories, with most plants located on land classified as cultivated crops (50.5%), grassland/herbaceous (20.9%), and shrubland/scrubland (14%) cover types that are associated with rangeland and cropland uses (table 1). Among the plants whose primary cover type is forest, deciduous forest is the most commonly observed type (7.6% nationally). Relative to other land cover types, deployment on cropland has generally increased through time, with an increasing proportion of footprint expansion occurring on cultivated cropland through 2020 (figure 4). Wind plant deployment on shrubland/scrubland cover largely occurred prior to 2016 and has since leveled off, reflecting that recent expansion of the wind power footprint has been concentrated within the Great Plains and South Central regions.

2.7. Integration of wind power into the built environment

Public acceptance is widely acknowledged as a key factor in determining the outcomes of wind project planning processes (Devine-Wright 2005, Enevoldsen and Valentine 2016) and could be linked to the perceived integration of turbines within the landscape (Petrova 2013, Firestone et al. 2018). As residences and built structures reflect an extent and form of human use, assessing and monitoring proximity between wind turbines and built structures provides a means to characterize and observe interactions between wind power and society. Proximity considerations have been explored in the past as a means to understand sentiments (Hoen et al. 2019) and to explore potential drivers and considerations.
Figure 3. Total footprint of contemporary wind energy deployment across major land use categories. Land use classifications from NLUD are informed using multiple data sources including census, land cover, and ownership information and reflect primary use types. Footprints are derived using turbine layouts and are adjusted to remove spatial overlap in cases where wind plant boundaries intersect. The “other” category includes commercial, general, industrial, residential, timber, and transportation uses, which have a combined footprint of 17.5 km$^2$. Not shown are states with footprints less than 5 km$^2$: Delaware, Connecticut, New Jersey, Rhode Island, and Tennessee.

in wind facility repowering (Kitzing et al 2020). To contextualize these spatial interactions, we compute the proximity of wind turbines to built structures using a comprehensive database containing more than 125 million building footprints in the United States (US Building Footprints 2018). We focused our analysis on residential structures by applying size thresholds to exclude features that were likely either too small (e.g. agricultural facilities) or too large (e.g. industrial or operational & maintenance buildings) to be considered primarily for residential use based on habitable area (Huang et al 2020). Note that our results represent a snapshot in time for both turbines and structures, which allows us to evaluate their co-occurrence without addressing the sequencing of construction. In addition, although we attempted to isolate residential structures by excluding buildings less than 50 m$^2$ and greater than 5000 m$^2$, our resulting database could encompass similarly sized agricultural facilities, which could conceivably mean that turbines are spaced farther from occupied dwellings than our results indicate.

Our analysis finds that turbines are commonly situated within the built environment, with 65% of all turbines located within one kilometer of a structure. However, local exposure to wind power projects is highly regional, as measured through turbine proximities. For example, turbines in the Great Lakes, Great Plains, and Northeast regions tend to be in closest proximity to built structures, with mean distances of 496, 702, and 887 m, respectively. In other regions, wind deployment occurs in less developed settings, as evidenced by more remote turbine placement in the South Central (1170 m), Pacific (1179 m), Mountain (1492 m), Southeast (1709 m), and Southwest regions (1514 m). Still, 70% of wind plants nationally have at least one turbine that is within 300 m of a built structure. The share of wind plants with similarly adjacent structures is greatest for the Great Lakes (89%) and least for the Southwest (43.3%).

In investigating whether turbine-structure proximities have changed over time, we did not find evidence of a consistent increase or decrease in proximities across all regions of the country. In the Great Lakes and Northeast regions, however, proximities have generally decreased since 2000. Conversely, we found that for the Mountain and South Central
regions, proximities generally increased during 2000–2020 with the largest change in median proximity occurring between 2000 and 2009. A detailed analysis of the regional trends in turbine proximities is provided in the Supplemental Information (figures S2 and S3).

2.8. Future deployment trajectories predispose grassland biome to continued expansion of wind power

Management of land use impacts of wind power and other renewables has long been an important issue in realizing clean energy goals (Pasqualetti 2000, US Department of Energy (DOE) 2008, Trainor et al 2016). To date, characterization of risks has largely focused on wildlife and social concerns at the project level and has not addressed the mounting cumulative footprint. Our approach differs from previous work to estimate the current and potential future cumulative footprint of wind power across the United States in two critical ways; first, by characterizing deployment across terrestrial biomes for ecological context, and second, by informing spatial projections of future wind deployment that reflect observed variability in regional wind plant capacity densities. Below, we quantify the extent of wind deployment on ecologically-relevant biomes, beginning with current deployment and proceeding with an investigation into how the cumulative wind power footprint could expand under a deep decarbonization scenario given recent trajectories for land requirements.

Nationwide, we estimate that the cumulative footprint of wind plants spans more than 46,915 km$^2$, an area equivalent in size to the combined land area of New Hampshire and Vermont. Disaggregated by biome type, we find that most historical wind plant deployment (81.1% of the national footprint) has occurred on temperate grassland, representing more than 38,064 km$^2$ (1.2% of biome extent). These results are consistent with the fact that grassland dominates much of the nation’s windiest regions in the interior. In absolute terms, we find that the footprint of current wind energy deployment on other biomes is considerably less (figure 5), with the temperate broadleaf and mixed forest biome experiencing the second largest footprint (4240 km$^2$).

Area estimates are adjusted to avoid double counting in cases where wind plant footprints overlap (see section 4).
Figure 5. Current and projected footprint of wind power on the nation’s biomes. The footprint represents total area contained within the outermost boundary of the wind plant and accounts for required spacing between turbines. These areas are meaningful for thinking about the lands and systems needed to support wind deployment. Generally, the extent of directly impacted lands, however, is a small fraction, typically around 1%–4%, and sometimes considerably less, of the overall footprint of wind energy systems. Symbols are sized proportionately to reflect the share of the biome’s extent within the contiguous United States that is projected to intersect with the wind power footprint. The 1:1 line demarcates equal areas along each axis. Map shows projected wind plant build-out locations and sizes. Projections are for cumulative onshore wind power deployment by 2050 based on a deep decarbonization scenario to reduce 95% of carbon emissions in the power sector (Mai et al. 2021). Biomes are sourced from (Dinerstein et al. 2017).

accounting for 0.2% of the biome’s area. Other biomes have been subjected to less extensive wind energy deployment, including deserts and xeric shrubland (2446 km²); temperate conifer forests (397 km²; 0.03% of biome extent); and Mediterranean forests, woodland, and scrubland (231 km²; 0.2% of biome extent). Wind deployment in tropical and subtropical grassland, savannas, and shrubland (1536 km²) has absorbed the largest share of any biome (2.1% of biome extent).

The cumulative footprint of wind power could grow substantially larger under future decarbonization projections (figure 5). For instance, referencing 721 GW of wind energy projected to be deployed by 2050 (Mai et al. 2021), and drawing on the interquartile range of recent (2019–2020) regional capacity densities, the total onshore wind footprint could encompass a future land area between 211 767 km² (75th percentile capacity density) and 348 036 km² (25th percentile), resulting in a 351%–642% increase over the existing footprint, respectively.

For the lower capacity densities (25th percentile), the 2050 projected footprint is slightly less than the land area of Montana. If 1%–4% of that footprint were directly impacted, that would be equivalent, in a highly dispersed form, to the land area ranging from roughly the size of Rhode Island to that of Connecticut. Biomes projected to have the largest interface with wind power in this specific scenario include temperate grasslands, savannas and shrublands (184 650 km²) as well temperate broadleaf and mixed forests (110 575 km²). In absolute terms, the projected footprint is smallest for Tropical & Subtropical Coniferous Forests (218 km²) and Mediterranean Forests, Woodlands & Scrub (753 km²). Nonetheless, by 2050, the projected footprint of wind power is considerable on a proportionate basis for all biomes, spanning on average 3.6% of each biome’s extent within the contiguous United States. For each of the two most expansive biomes, temperate grasslands, savannas and shrublands (3122 644 km²) and temperate broadleaf & mixed forests (1885 167 km²), the
future wind footprint could span nearly 6% of their national extent.

While our use of the Mai et al. (2021) scenario provides a lens through which to evaluate potential risks to ecosystems, there are wide uncertainties around the placement and intensity of future wind facilities that must be acknowledged. Assumptions around land access, capacity factor improvements, energy generation cost, transmission expansion, policy, and more (as explored in Mai et al. 2021) can influence the future spatial distribution of wind facilities. Further, uncertainties regarding end-use efficiency, demand, and electrification could significantly affect the quantities and locations of wind deployment. Our intent in selecting a single scenario is not to be overly precise in analyzing a specific future but rather to expose the scale of potential ecological implications that may arise under a scenario where wind power plays a leading role in the future energy system. The chosen scenario represents a largely (95%) decarbonized electricity system in which wind technology plays a prominent role, but is bounded by existing land-use accessibility, modest technological advancements, and modest cost reductions.

3. Discussion

With more than 106 GW of operating wind power in the U.S. and an average power density of approximately 1 MWe km$^{-2}$, the landscape impacts of wind energy are diffuse yet sizable. Extending beyond static characterizations, we find that the relationship between wind energy and the landscape is spatially and temporally variable. Regional deployment characteristics such as capacity density drive differences both in required land areas as well as the mix of different land use/cover types. Technology-driven mediation of landscape interactions provides opportunity for wind energy technology and plants to be adapted to serve broader sustainability objectives.

Key outcomes from our work include findings on observed local and regional clustering in wind energy deployments to date, sizable growth in plant sizes, and new insights into the scale and magnitude of wind power interactions with social and ecological systems. Additionally, despite falling wind plant capacity densities, power densities are stable or potentially increasing. We also observe that most historical U.S. wind deployment has been confined to the temperate grassland biome in the nation’s interior, and wind plants are being increasingly developed on land already disturbed by human activities (i.e. cropland) (Fletcher et al. 2011). Still, our analysis of landscape interactions highlights the potential for wind energy deployment to function synergistically with cropland or other disturbed lands—a deployment strategy that could help to mitigate cumulative impacts to wildlife (Kieseecker et al. 2011, Milbrandt et al. 2014).

These patterns could change under future decarbonization scenarios. Such scenarios examine plausible technological pathways based on policy considerations such as land access among many other factors, yielding varying spatial distributions and intensities of wind deployment. However, given a common objective of decarbonization, all scenarios reveal a need for hundreds of gigawatts of additional wind deployment with deployment occurring across most of the United States. For instance, the specific Mai et al. (2021) scenario examined here suggests the potential for increased deployment in forested biomes, which could potentially contribute to habitat fragmentation. Finally, we find that wind power frequently exists proximate to structures, suggesting that landscape level impacts on sustainability are not limited to wind energy infrastructure in a vast majority of locations where wind energy is deployed to date. Therefore, deeper acknowledgement of the degree to which wind power contributes to cumulative anthropogenic disturbances across the landscape is increasingly needed.

Accordingly, while questions around the potential saturation of wind power have been driven heavily by inter-plant wake interactions (Lundquist et al. 2019) and transmission congestion (Jorgensen et al. 2017), looking ahead, social (Firestone et al. 2019) and ecological considerations for concentrated deployment are becoming increasingly prominent (Katzner et al. 2019). Nevertheless, technology advancement can help mitigate the potential risks of local and regional plant clustering by increasing the economic viability of lower quality wind resource sites and facilitating cost savings even in the absence of opportunities for economies of scale. These advancements could potentially support more resilient energy systems through geographic diversity of deployed power (Bloom et al. 2017). Although existing deployment patterns are largely driven by significantly better wind resource in the nation’s interior and are concentrated within private lands today, innovations and decarbonization policies that provide additional market momentum could open up new areas of the nation (Mai et al. 2021). Evolving federal priorities and policies could also affect deployment on public lands.

Notably, however, opportunities to reduce clustering might reinforce trends such as lower capacity densities. This dilutes the effect of wind turbines in any given location but might also increase the overall extent of the interface between wind turbines and the landscape with various ecological and social implications possible such as habitat fragmentation and visual impacts (Enevoldsen and Valentine 2016, Jacobson et al. 2017). At the same time, given the benefits of technology improvements to date, which have, based on our analysis, stabilized power density trends, there is the potential for innovation such as through turbine scaling (Wiser and Bolinger 2019, Wiser et al. 2020b) to further mitigate these risks by maximizing energy densities with fewer turbines and less required...
capacity, even in locations with relatively lower wind resource quality.

Dynamic landscape interactions require continued tracking of the interface between wind energy and the landscape. Further research is also needed to precisely identify opportunities for technology and engineering-based mitigation. Given the varied nature of wind energy land use as well as the diverse technological options, decision-makers within the wind energy, conservation, and regulatory communities need to be well-informed about how deployment might affect their local context and what tools might be available to manage impacts. This base level of education should include ongoing tracking and trends reporting efforts to inform effective regulatory and policy decisions, particularly for land and resource managers as well as federal, state, and local decision-making officials. Accelerated research exploring the nature of these tradeoffs is also important given the time required to commercialize new turbine technologies and innovations. Due to the potential pace of development and length of involved planning processes, such work is urgently needed to effectively manage wind power for social, climate, and ecological outcomes.

A recent synthesis highlighted grand challenges in the science of wind energy that require interdisciplinary progress to meet expansion goals (Vees et al 2019). This vision embraces an integrative scientific approach, focusing on fusing disparate strands of knowledge from physical, technological, and economic disciplines. Although these challenges are clearly important, the scale of potential wind deployments in the future power system suggest that they must be addressed alongside social (Firestone 2019) and ecological (Katzner et al 2019) dimensions. Given the distinctively geographic nature of these sustainability considerations, advancing a deeper understanding of the spatial context in which wind energy deployment is unfolding will be critical to anticipate, inform and mitigate challenges of an expanding wind energy portfolio.

4. Methods

4.1. Wind plant representation

Spatial data on wind turbine installations were provided by the U.S. Wind Turbine Database (UWSTDB) (Hoen et al 2018). The USWTDB contains wind plant project information and technical specifications for more than 65,000 turbines operational as of October 2020. Turbines were grouped into distinct wind plants according to a unique project identifier provided by the USWTDB. For each wind plant ($n = 1089$), we derived project-level properties describing the number of turbines, technology parameters, installed capacity, and year of operation.

4.2. Footprint area estimation

Central to the understanding of land use issues surrounding wind power is the notion that wind plants occupy area. Although this is conceptually straightforward, in practice the delineation of the wind plant footprint is challenging for several reasons. Owing to their discontinuous nature, wind plants lack distinctive visual boundaries that can be used to infer the extent of a project. In the absence of this information, two general approaches have served as guiding principles for quantifying wind plant area and related metrics. The first represents an evaluation of area that has been directly disturbed or transformed by wind plant development and is termed ‘direct impact area.’ The second approach captures the ‘total area’ of all land more broadly associated with a wind plant (Denholm et al 2009), which we refer to as the ‘footprint’—the fully inclusive area spanned by the outermost turbines. Each measure of wind plant area is useful for different purposes, but they must be clearly distinguished.

There are important quantitative and qualitative differences between these definitions. In terms of spatial extent, direct impact area represents a small subset of total area, typically a small fraction of total wind plant area. In addition, direct impact areas are subject to a higher degree of wind energy transformation than the corresponding total area. Direct impact areas include observable features—such as service roads, turbine pads, transmission lines and clearings—that can be quantified using digitization techniques (Jones and Pejchar 2013, Diffendorfer and Compton 2014). Such efforts require manually intensive human interpretation and were beyond the scope of this analysis. In contrast, the footprint is generally more difficult to quantify given that wind plant boundaries are not readily discernible from imagery and lack defining features that could be used to delineate a project perimeter. In some cases, project boundaries might be included in official legal and land lease documentation; however, this information is incomplete and inconsistent. In the absence of standardized documentation, no uniform definition of footprint has emerged. Determining the footprint area, however, is required to evaluate land use metrics for wind power including capacity density and power density and to quantify the extent of potential interactions with the social and ecological environment (though not in terms of directly impacted area).

We use an established geometric approach to delineate the boundaries of the footprint as informed by the spatial configuration of turbines. As a first step, we apply to turbines a buffer distance of 300 m to reflect typical setback considerations (Aydin et al 2010). Second, we construct a convex hull geometry around the buffered features, producing a minimally bounding polygon that encompasses all turbines. The
geometry described by the convex hull polygon represents the footprint. An example illustration of buffer and convex hull spatial units is provided in the Supplemental Information (figure S4).

In some cases, the convex hull methodology produces polygons with spatial overlap among adjacent wind plants. To avoid double counting land area that would otherwise be captured independently for each wind plant, we merge overlapping wind plants to produce a refined set of boundaries used to delineate total wind plant footprint. This procedure eliminated 3358 km$^2$ of duplicative land area. We use this set of dissolved boundaries as the basis for all inferences regarding cumulative footprint. Individual (non-merged) project boundaries are used to establish wind plant characteristics and thus would account for any discrepancies in reported land use/land cover composition. While our method is based on an established geometric approach, other methods for estimating wind plant boundaries exist. For example, Miller and Keith (2018) demonstrate two alternative approaches, one that applies an 8-rotor diameter (D) buffer around each turbine and the other using Voronoi polygons to delineate the ground surface area of each turbine. A direct comparison between our methodology and those illustrated by Miller and Keith reveals similar results for two selected wind plants. Bull Creek is a 180 turbine, 180 MW capacity plant that we estimate has a footprint of 51.1 km$^2$, while Miller and Keith estimate an area of 47.8 km$^2$ (8D buffer) and 54 km$^2$ (Voronoi polygon). Fenton Wind Farm is a 137 turbine, 205.5 MW capacity plant that we estimate has a footprint of 97.5 km$^2$; Miller and Keith estimate an area of 100 km$^2$ (8D buffer) and 137 km$^2$ (Voronoi polygon).

Using legal documents to ascertain plant boundaries, Denholm et al (2009) produced estimates of plant area that are larger than indicated by our methods for these two plants (Bull Creek 243 km$^2$ and Fenton Wind Farm 156 km$^2$). Though this may suggest that area estimates produced by the uniform methods are conservative compared to legal descriptions, further research is needed to tease out whether such differences are observed consistently across plants and would yield systematic biases.

4.3. Spatial analysis
We assess wind energy deployment using a spatially explicit characterization methodology consisting of geospatial modeling, data integration and analysis. Our aim here is not to quantify land transformation associated with wind energy that would otherwise be captured by a direct impact assessment (e.g. Jones and Pejchar 2013, Diffendorfer et al 2019), but rather to ascertain critical information about the nature and character of wind energy deployment as it has played out within United States during the past two decades.

Recognizing that formal ecological assessment requires localized information that is beyond the scope of the present study, we instead focus on two high-level components of ecological systems that are relevant to the national perspective. First, to assess how wind energy development has proceeded across terrestrial habitat types, we acquired spatial information for the distribution of major biomes (Dinerstein et al 2017). Biomes are defined based on ecological communities that share similar characteristics. Second, we rely on land cover proxies to infer biophysical attributes of the environments where wind power deployment has occurred.

In investigating the social backdrop of energy deployment, we differentiate between land cover as a physical descriptor and land use as a social phenomenon. Land cover refers to observable biophysical attributes of the earth's surface, whereas land use describes human activities that occur on the land surface that could in turn modify land cover (Verburg et al 2009, Theobald 2014). Land use classification systems provide a functional view of the earth's surface that is valuable for characterizing working landscapes. Land use and cover attributes were characterized at the wind plant level using convex hull project boundaries for conducting zonal statistics. Land cover data is sourced from the national land cover database (NLCD; Yang et al 2018). Land use data is obtained from the national land use dataset (NLUD; Theobald 2014). Spatial analysis was performed using Google Earth Engine (Gorelick et al 2017) and open-source packages (Python 2019).

We analyze the proximity of wind plants to built structures using a comprehensive data set of building footprints (US Building Footprints 2018). For each turbine, we compute the straight-line distance to its nearest structure.

We analyze wind plant clustering by computing distances between neighboring wind plants. For this, we computed straight-line distances between all pairs of wind plants, finding the neighboring plant with the minimum hull-to-hull distance. Note that we did not differentiate between upwind and downwind plants as that would require detailed meteorological assessment.

4.4. Trends
We use linear regression to model annual changes in fleet-wide capacity density as a function of specific power and capacity. We include capacity as an explanatory term because its omission could otherwise confound insights into the relationship between specific power and capacity density that both relate to capacity. First, we transform plant-level observations of capacity density and specific power into an annual series of capacity-weighted averages. Yearly average capacity densities are also obtained. Second, prior to specifying the model, we de-trend both independent...
and dependent variables by differencing them against samples from the previous year. The model is then approximated using least squares regression.

4.5. Land use intensity
As a metric that accounts for both the magnitude of the occupied area that is directly impacted and the duration of the occupation, we calculate land use intensity to capture how wind energy production scales with direct land usage over the lifetime of a turbine asset. Additionally, this information can be used to support equivalent comparisons with other technologies whose generating lifetimes may vary considerably. To derive the directly impacted area ($A_{DI}$), we use recent findings from (Diffendorfer et al. 2019) that generalize the extent of directly impacted area, measured in hectares, relative to the installed capacity of a wind plant.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions

D H A: conceptualization, methodology, writing—original draft, writing—review & editing, formal analysis, visualization; A L: conceptualization, validation, visualization, writing—original draft, writing—review & editing, funding acquisition; E L: writing—review & editing, funding acquisition.

Conflict of interest

The authors declare no competing interests.

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