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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 ($\sim$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:

$$CD = \frac{C}{A}, \tag{1}$$

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:

$$PD = \frac{C * cf}{A} \tag{2}$$

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:

$$ED = \frac{C * cf * H}{A}, \tag{3}$$

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:

$$LUI = \frac{A_D}{C * cf * H * y}, \tag{4}$$

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 (Kiesecker *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

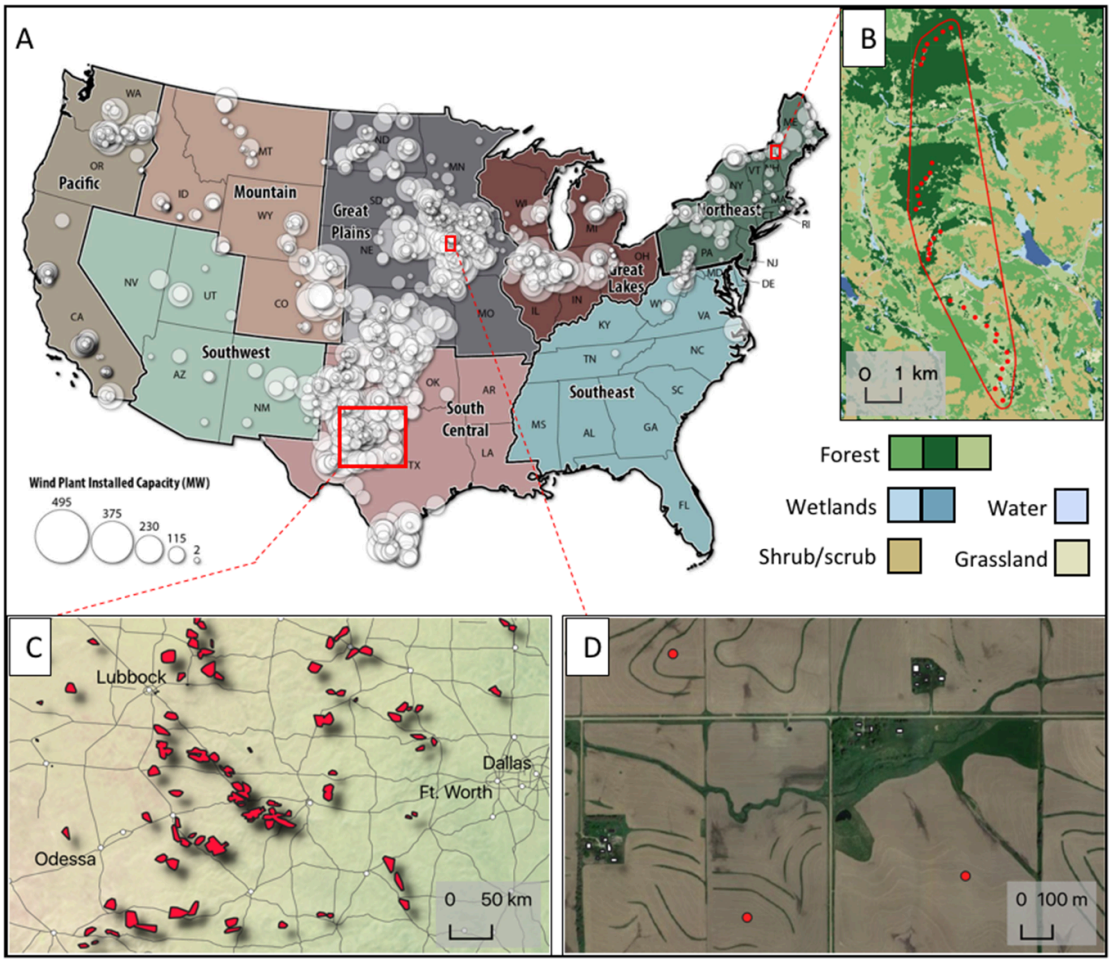

Figure 1. Tracking the sustainability implications of expanding wind power requires integrated knowledge across spatial scales. (A) National distribution of wind projects greater than 2 MW and operational as of mid-2020 (turbine-level data provided by the U.S. Wind Turbine Database (USWTDB)). (B) Localized environmental impacts of wind deployment must be weighed alongside cumulative risks and benefits to inform broader opportunities and tradeoffs (turbines and project footprint shown in red on top of land cover map for a wind plant in the Northeast). (C) Concentrated deployment of wind power in regions with favorable conditions exposes emerging geographic challenges under continued expansion (clustering of existing wind plants shown here for Texas). (D) The distributed nature of wind energy sets the stage for social and ecological interactions that drive potential land use conflicts and synergies. Turbines (in red) are embedded within complex landscapes, oftentimes interfacing with agricultural and residential uses as shown here.

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 ($n = 266$, MW = 37 192) and Great Plains ($n = 315$, MW = 29 722) regions that span the wind belt. Considerable development has also occurred in the Great Lakes ($n = 121$, MW = 11 877), Pacific ($n = 134$, MW = 11 570), Mountain ($n = 92$, MW = 7547), and Northeast ($n = 112$, MW = 4682) regions. In comparison, the Southwest ($n = 31$, MW = 2757) and Southeast regions ($n = 18$, MW = 1348) 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[3]. 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 (km^2). 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 km^2. 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 $\sim$0.06 $\times$ specific power $-$0.03 $\times$ capacity $+$0.55). We include capacity as an additional explanatory term to account for its

[3] In the data we assessed, wind plants are defined by their regulatory filings, which although imperfect as an analytical unit still provide useful perspective, especially when coupled with the clustering trends noted above.

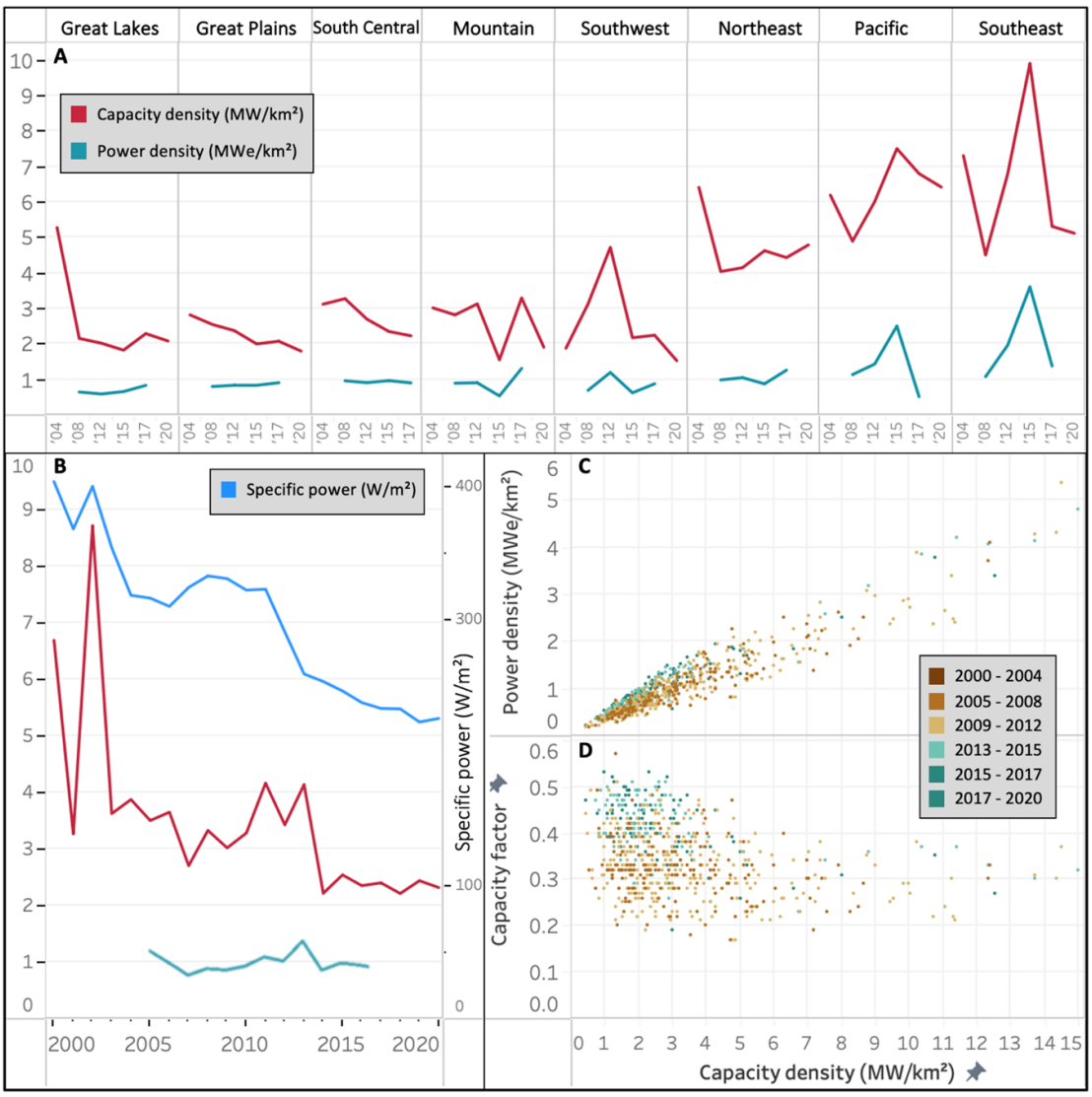

Figure 2. Regional (A) and national (B) trends in wind plant capacity density (MW km^{-2}) and average power density (MWe km^{-2}) for projects greater than 2 MW deployed between 2000 and 2020[4]. Results in A are presented as capacity-weighted averages for plants in multiyear increments (2000–2004, 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.

[4] Information on capacity factor and power density was limited to plants built between 2005 and 2017 because of data availability.

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 (Kuvlesky *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

(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 constructure 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-constructure 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 $\pm$ 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).

	Number of plants	Installed capacity (MW)
Land use category (NLUD, Level 2)		
Cropland	527	55 664
Rangeland	490	49 146
Residential	17	102
Public	12	929
Industrial	11	48
Park	9	379
Commercial	6	29
Institutional	5	14
Timber	4	79
General	2	10
Natural area	2	69
Wetland	1	215
Transportation	1	2
Private easement	1	5
Land cover class (NLCD)		
Cultivated crops	550	58 115
Grassland/herbaceous	228	24 026
Shrub/scrub	153	17 256
Deciduous forest	83	4229
Pasture/hay	29	1588
Evergreen forest	14	647
Barren land	11	455
Developed, medium intensity	6	16
Developed, high intensity	5	16
Mixed forest	4	107
Developed, low intensity	2	5
Emergent herbaceous wetland	2	10
Woody wetland	1	215

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

[5] The park land use category contains natural, urban, and undifferentiated parks.

[6] Easements are considered legal arrangements as opposed to a distinct land use type.

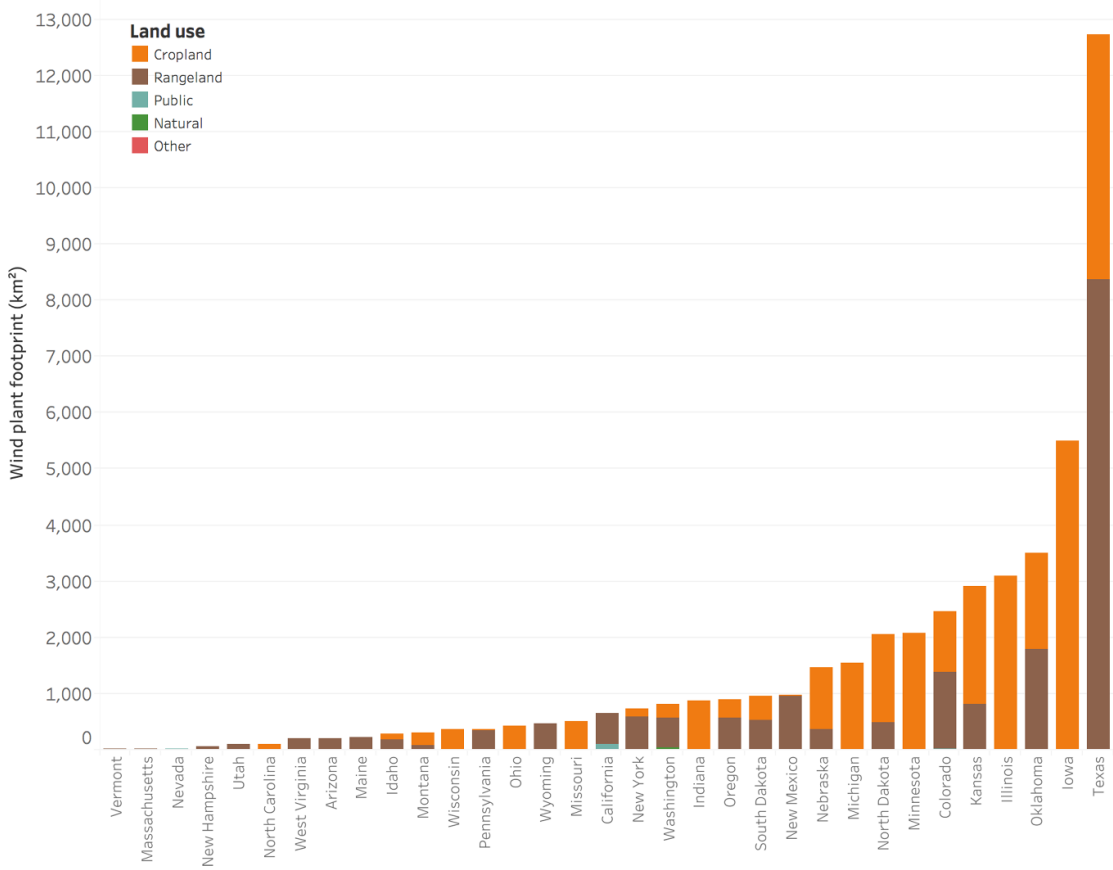

Figure 3. Total footprint of contemporary wind energy deployment across major land use categories. Land use classifications from NLUD are informed using multiple data sources including census, land cover, and ownership information and reflect primary use types. Footprints are derived using turbine layouts 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

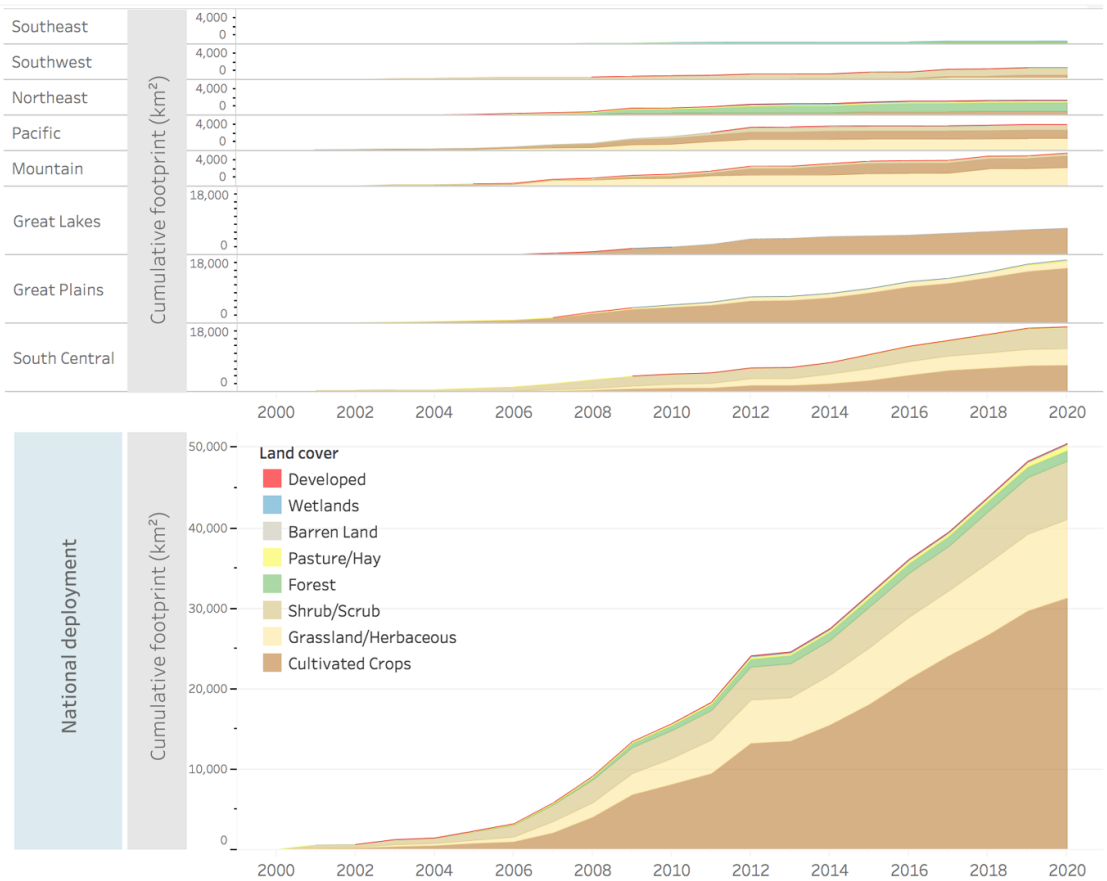

Figure 4. Cumulative footprint of wind power on major land cover types in the United States for deployment occurring between 2000 and 2020. Regional contributions to the national footprint are shown above. For visual clarity, the Mountain, Pacific, Northeast, Southwest, and Southeast regions are shown using a reduced *y*-axis range relative to the South Central, Great Plains, and Great Lakes regions, which cover most (80.3%) of the national footprint as of 2020.

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[7] 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),

[7] Area estimates are adjusted to avoid double counting in cases where wind plant footprints overlap (see section 4).

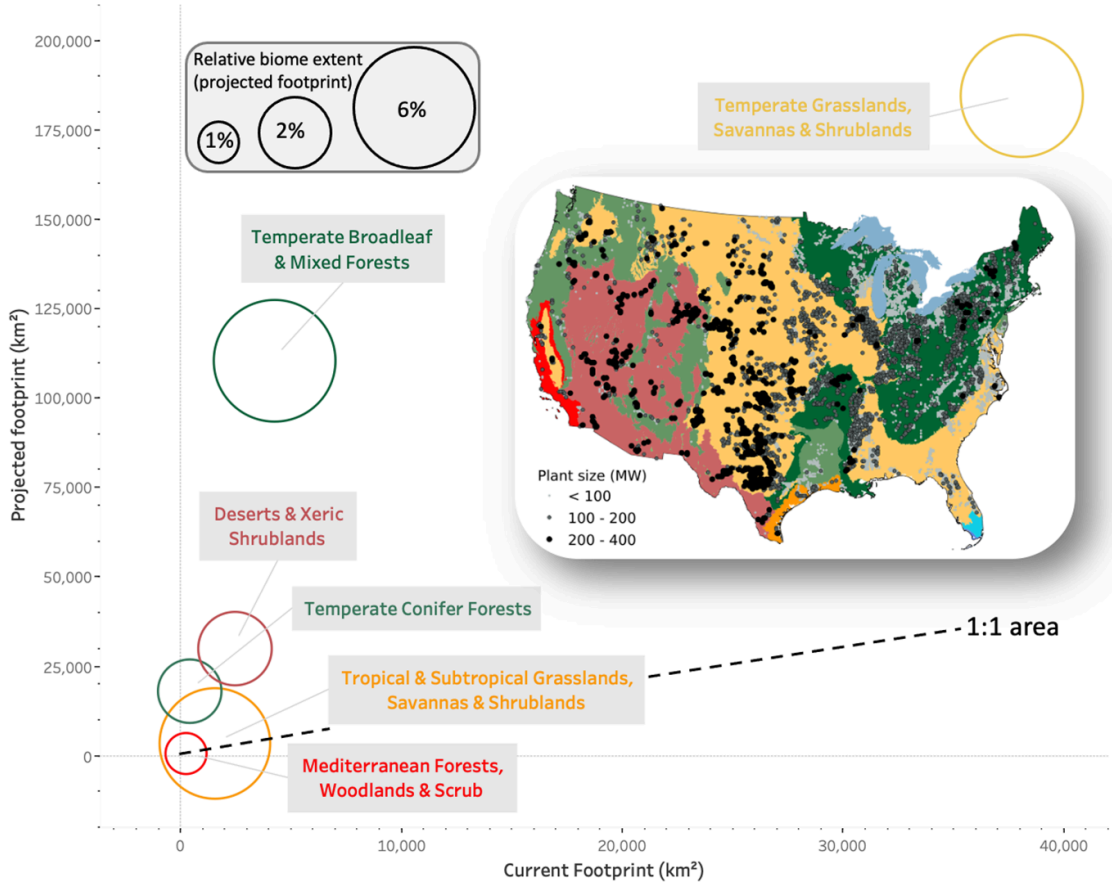

Figure 5. Current and projected footprint of wind power on the nation's biomes. The footprint represents total area contained within the outermost boundary of the wind plant and accounts for required spacing between turbines. These areas are meaningful for thinking about the lands and systems needed 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 km^2); temperate conifer forests (397 km^2; 0.03% of biome extent); and Mediterranean forests, woodland, and scrubland (231 km^2; 0.2% of biome extent). Wind deployment in tropical and subtropical grassland, savannas, and shrubland (1536 km^2) 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 km^2 (75th percentile capacity density) and 348 036 km^2 (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 km^2) as well temperate broadleaf and mixed forests (110 575 km^2). In absolute terms, the projected footprint is smallest for Tropical & Subtropical Coniferous Forests (218 km^2) and Mediterranean Forests, Woodlands & Scrub (753 km^2). 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 km^2) and temperate broadleaf & mixed forests (1885 167 km^2), 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 (Kiesecker *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 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 (Veers *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_D), 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

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References

Aydin N Y, Kentel E and Duzgun S 2010 GIS-based environmental assessment of wind energy systems for spatial planning: a case study from Western Turkey *Renew. Sustain. Energy Rev.* **14** 364–73

Bloom A, Helman U, Holttinen H, Summers K, Bakke J, Brinkman G and Lopez A 2017 It's indisputable: five facts about planning and operating modern power systems *IEEE Power Energy Mag.* **15** 22–30

Bridge G, Bouzarovski S, Bradshaw M and Eyre N 2013 Geographies of energy transition: space, place and the low-carbon economy *Energy Policy* **53** 331–40

Brown P R and Botterud A 2020 The value of inter-regional coordination and transmission in decarbonizing the US electricity system *Joule* 5 115–34

Bunzel K, Bovet J, Thrän D and Eichhorn M 2019 Hidden outlaws in the forest? A legal and spatial analysis of onshore wind energy in Germany *Energy Res. Soc. Sci.* **55** 14–25

Cole W, Corcoran S, Gates N, Mai T and Das P 2020 2020 standard scenarios report: a US electricity sector outlook (available at: www.nrel.gov/docs/fy21osti/77442.pdf)

Copeland H E, Pocewicz A and Kiesecker J M 2011 Geography of energy development in western North America: potential impacts on terrestrial ecosystems *Energy Development and Wildlife Conservation in Western North America* (Washington, DC: Island Press) p 16

Denholm P, Hand M, Jackson M and Ong S 2009 Land use requirements of modern wind power plants in the United States (Golden, CO: National Renewable Energy Lab. (NREL)) (available at: www.osti.gov/biblio/964608)

Devine-Wright P 2005 Beyond NIMBYism: towards an integrated framework for understanding public perceptions of wind energy *Wind Energy* **8** 125–39

Diffendorfer J E and Compton R W 2014 Land cover and topography affect the land transformation caused by wind facilities *PLoS One* **9** e88914

Diffendorfer J E, Dorning M A, Keen J R, Kramer L A and Taylor R V 2019 Geographic context affects the landscape change and fragmentation caused by wind energy facilities *PeerJ* **7** e7129

Dinerstein E *et al* 2017 An ecoregion-based approach to protecting half the terrestrial realm *Bioscience* **67** 534–45

Enevoldsen P and Jacobson M Z 2021 Data investigation of installed and output power densities of onshore and

offshore wind turbines worldwide *Energy Sustain. Dev.* **60** 40–51
Enevoldsen P and Valentine S V 2016 Do onshore and offshore wind farm development patterns differ? *Energy Sustain. Dev.* **35** 41–51
Fargione J, Joseph Kiesecker M, Slaats J and Olimb S 2012 Wind and wildlife in the northern great plains: identifying low-impact areas for wind development *PLoS One* **7** e41468
Firestone J 2019 Wind energy: a human challenge *Science* **366** 1206
Firestone J, Hoen B, Rand J, Elliott D, Hübner G and Pohl J 2018 Reconsidering barriers to wind power projects: community engagement, developer transparency and place *J. Environ. Policy Plan.* **20** 370–86
Fletcher R J Jr, Robertson B A, Evans J, Doran P J, Alavalapati J R R and Schemske D W 2011 Biodiversity conservation in the era of biofuels: risks and opportunities *Front. Ecol. Environ.* **9** 161–8
Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D and Moore R 2017 Google earth engine: planetary-scale geospatial analysis for everyone *Remote Sens. Environ.* **202** 18–27
Harrison-Atlas D, Maclaurin G and Lantz E 2021 Spatially-explicit prediction of capacity density advances geographic characterization of wind power technical potential *Energies* **14** 3609
Hayes M A *et al* 2019 A smart curtailment approach for reducing bat fatalities and curtailment time at wind energy facilities *Ecol. Appl.* **29** 4
Hoen B, Diffendorfer J E, Rand J, Kramer L A, Garrity C P, Roper A D and Hunt H. 2018 United States wind turbine database (ver. 3.2, October 2020) *US Geological Survey* (https://doi.org/10.5066/F7TX3DN0)
Hoen B, Firestone J, Rand J, Elliot D, Hübner G, Pohl J, Wiser R, Lantz E, Haac T R and Kaliski K 2019 Attitudes of U.S. wind turbine neighbors: analysis of a nationwide survey *Energy Policy* **134** 110981
Huang X, Wang C, Li Z and Ning H 2020 A 100 m population grid in the CONUS by disaggregating census data with open-source Microsoft building footprints *Big Earth Data* **5** 112–33
International Energy Agency (IEA) 2018 World energy outlook 2018 (Paris) (https://doi.org/10.1787/weo-2018-en)
Ioannidis R and Koutsoyiannis D 2020 A review of land use, visibility and public perception of renewable energy in the context of landscape impact *Appl. Energy* **276** 115367
Jacobson M Z *et al* 2017 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world *Joule* **1** 108–21
Johnson G D, Erickson W P, Dale Strickland M, Shepherd M F, Shepherd D A and Sarappo S A 2003 Mortality of bats at a large-scale wind power development at buffalo ridge, Minnesota *Am. Midl. Nat.* **150** 332–42
Jones N F and Pejchar L 2013 Comparing the ecological impacts of wind and oil & gas development: a landscape scale assessment *PLoS One* **8** e81391
Jordaan S M, Heath G A, Jordan Macknick B W, Bush E M, Ben-Horin D, Urrea V and Marceau D 2017 Understanding the life cycle surface land requirements of natural gas-fired electricity *Nat. Energy* **2** 804–12
Jorgensen J, Mai T and Brinkman G 2017 *Reducing Wind Curtailment through Transmission Expansion in a Wind Vision Future No. NREL/TP*-6A20-67240 (Golden, CO: National Renewable Energy Lab. (NREL))
Katzner T E *et al* 2019 Wind energy: an ecological challenge *Science* **366** 1206–7
Kiesecker J M, Evans J S, Fargione J, Kevin Doherty K R, Foresman T H, Kunz D N, Nibbelink N P and Niemuth N D 2011 Win-win for wind and wildlife: a vision to facilitate sustainable development *PLoS One* **6** e17566
Kitzing L, Jensen M K, Telsnig T and Lantz E 2020 Multifaceted drivers for onshore wind energy repowering and their implications for energy transition *Nat. Energy* **5** 1012–21
Kunz T H, Arnett E B, Erickson W P, Hoar A R, Johnson G D, Larkin R P, Dale Strickland M, Thresher R W and Tuttle M D 2007 Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses *Front. Ecol. Environ.* **5** 315–24
Kuvlesky W P Jr, Brennan L A, Morrison M L, Boydston K K, Ballard B M and Bryant F C 2007 Wind energy development and wildlife conservation: challenges and opportunities *J. Wildl. Manage.* **71** 2487–98
Larson E *et al* 2020 Net-zero America: potential pathways, infrastructure, and impacts, interim report (Princeton, NJ: Princeton University) (available at: https://netzeroamerica.princeton.edu) (Accessed 15 December)
Lopez A, Mai T, Lantz E, Harrison-Atlas D, Williams T and Maclaurin G 2021 Land use and turbine technology influences on wind potential in the United States *Energy* **223** 120044
Lovins A B 2011 Renewable energy's 'footprint' myth *Electr. J.* **24** 40–47
Lundquist J K, DuVivier K K, Kaffine D and Tomaszewski J M 2019 Costs and consequences of wind turbine wake effects arising from uncoordinated wind energy development *Nat. Energy* **4** 26–34
MacDonald A E, Christopher T M, Clack A A, Dunbar A, Wilczak J and Xie Y 2016 Future cost-competitive electricity systems and their impact on US CO2 emissions *Nat. Clim. Change* **6** 526–31
Mai T, Lopez A, Mowers M and Lantz E 2021 Interactions of wind energy project siting, wind resource potential, and the evolution of the U.S. power system *Energy* **223** 119998
Mai T, Wiser R, Sandor D, Brinkman G, Heath G, Paul Denholm D J, Hostick N D, Schlosser A and Strzepek K 2012 Renewable electricity futures study. Volume 1: exploration of high-penetration renewable electricity futures (https://doi.org/10.2172/1046880)
McDonald R I, Fargione J, Kiesecker J, Miller W M and Powell J 2009 Energy sprawl or energy efficiency: climate policy impacts on natural habitat for the United States of America *PLoS One* **4** e6802
McKenna R *et al* 2022 High-resolution large-scale onshore wind energy assessments: a review of potential definitions, methodologies and future research needs *Renew. Energy* **182** 659–84
Milbrandt A R, Heimiller D M, Perry A D and Field C B 2014 Renewable energy potential on marginal lands in the United States *Renew. Sustain. Energy Rev.* **29** 473–81
Miller L M and Keith D W 2018 Observation-based solar and wind power capacity factors and power densities *Environ. Res. Lett.* **13** 104008
Möller B 2010 Spatial analyses of emerging and fading wind energy landscapes in Denmark *Land Use Policy* **27** 233–41
Nitsch F, Turkovska O and Schmidt J 2019 Observation-based estimates of land availability for wind power: a case study for Czechia *Energy Sustain. Soc.* **9** 1–13
Pasqualetti M J 2000 Morality, space, and the power of wind-energy landscapes *Geogr. Rev.* **90** 381–94
Petrova M A 2013 NIMBYism revisited: public acceptance of wind energy in the United States *Wiley Interdiscip. Rev. Clim. Change* **4** 575–601
Rand J and Hoen B 2017 Thirty years of North American wind energy acceptance research: what have we learned? *Energy Res. Soc. Sci.* **29** 135–48
Rehbein J A, Watson J E M, Lane J L, Sonter L J, Venter O, Atkinson S C and Allan J R 2020 Renewable energy development threatens many globally important biodiversity areas *Glob. Change Biol.* **26** 3040–51
Rinne E, Holttinen H, Kiviluoma J and Rissanen S 2018 Effects of turbine technology and land use on wind power resource potential *Nat. Energy* **3** 494–500

Ryberg D S, Robinius M and Stolten D 2018 Evaluating land eligibility constraints of renewable energy sources in Europe *Energies* **11** 1246

Smil V 2008 *Energy in Nature and Society: General Energetics of Complex Systems* (Cambridge, MA: MIT Press) (https://doi.org/ 10.1063/1.3074266)

Theobald D M 2014 Development and applications of a comprehensive land use classification and map for the US *PLoS One* **9** e94628

Trainor A M, McDonald R I and Fargione J 2016 Energy sprawl is the largest driver of land use change in United States *PLoS One* **11** e0162269

Turkovska O, Castro G, Klingler M, Nitsch F, Regner P, Soterroni A C and Schmidt J 2021 Land-use impacts of Brazilian wind power expansion *Environ. Res. Lett.* **16** 024010

Turner B L, Moss R H and Skole D L 1993 *Relating Land Use and Global Land-Cover Change: A Proposal for an IGBP-HDP Core Project* 24 International Geosphere-Biosphere Program, Stockholm

United Nations (UN) 2015 Transforming our world: the 2030 agenda for sustainable development (available at: https://sdgs.un.org/2030agenda)

US Building Footprints 2018 Github (available at: https://github.com/microsoft/USBuildingFootprints) (Accessed 28 May 2020)

US Department of Energy (DOE) 2008 20% wind energy by 2030: increasing windenergy's contribution to U.S. electricity supply DOE/GO-102008-2567 (Golden, CO)

van Zalk J and Behrens P 2018 The spatial extent of renewable and non-renewable power generation: a review and meta-analysis of power densities and their application in the U.S *Energy Policy* **123** 83–91

Veers P *et al* 2019 Grand challenges in the science of wind energy *Science* **366** 6464

Verburg P H, Jeannette V D S, Veldkamp A and Willemen L 2009 From land cover change to land function dynamics: a major challenge to improve land characterization *J. Environ. Manage.* **90** 1327–35

Wachs E and Engel B 2021 Land use for United States power generation: a critical review of existing metrics with suggestions for going forward *Renew. Sustain. Energy Rev.* **143** 110911

Wang S and Wang S 2015 Impacts of wind energy on environment: a review *Renew. Sustain. Energy Rev.* **49** 437–43

Wiser R H *et al* 2020a.Wind technology data and trends: land-based focus, 2020 (Berkeley, CA: Lawrence Berkeley National Laboratory (LBNL))

Wiser R H and Bolinger M 2019 *2018 Wind Technologies Market Report* (Berkeley, CA: Lawrence Berkeley National Laboratory (LBNL))

Wiser R, Millstein D, Bolinger M, Jeong S and Mills A 2020b The hidden value of large-rotor, tall-tower wind turbines in the United States *Wind Eng.* **45** 857–71

Wolaver B D, Pierre J P, Labay B J, LaDuc T J, Duran C M, Ryberg W A and Hibbitts T J 2018 An approach for evaluating changes in land-use from energy sprawl and other anthropogenic activities with implications for biotic resource management *Environ. Earth Sci.* **77** 1–14

Wolsink M 2000 Wind power and the NIMBY-Myth: institutional capacity and the limited significance of public support *Renew. Energy* **21** 49–64

Wu G C, Leslie E, Oluwafemi Sawyerr D, Cameron R, Brand E, Cohen B, Allen D, Ochoa M and Olson A 2020 Low-impact land use pathways to deep decarbonization of electricity *Environ. Res. Lett.* **15** 074044

Xu K, Lingchao H, Hanjian H, Liu S, Yuanyuan D, Wang Z, Yan L, Liyan L, Khan A and Wang G 2019 Positive ecological effects of wind farms on vegetation in China's Gobi desert *Sci. Rep.* **9** 1–11

Yang L *et al* 2018 A new generation of the united states national land cover database: requirements, research priorities, design, and implementation strategies *ISPRS J. Photogramm. Remote Sens.* **146** 108–23

Zaunbrecher B S, Daniels B, Roß-Nickoll M and Ziefle M 2018 The social and ecological footprint of renewable power generation plants. Balancing social requirements and ecological impacts in an integrated approach *Energy Res. Soc. Sci.* **45** 91–106