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Land use and turbine technology influences on wind potential in the United States

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ABSTRACT

As clean energy ambitions have expanded, critically evaluating renewable energy supply has become increasingly important to the energy research community and stakeholders. This study examines the onshore wind resource potential for the conterminous United States and its sensitivity to siting constraints and turbine technology innovation. We compile localized regulatory information and use high-resolution data to present multiple siting regimes covering relatively constrained to unconstrained potentials. Our efforts reveal high sensitivity to these variables and sizable uncertainty in the overall wind energy resource potential. Specifically, we find that siting constraints may shift the total capacity available to commercial wind energy by 2.3–15.1 TW. Furthermore, our results illustrate that technology advancement could require larger setbacks from buildings and infrastructure, reducing the total available capacity potential by 20% relative to estimates using current technology, but that this reduction is largely offset by increased generation such that the net effect on generation is 1%. The observed sensitivity to and uncertainty resulting from the variables we analyze suggest there is value in continued study and development of increasingly sophisticated approaches to characterizing wind resource potential.

1. Introduction

Energy modelers and decision makers have begun exploring scenarios with levels of operating wind power in the energy sector that approach, and in some cases, exceed 40% of the electricity supply in the United States [1–4]. These scenarios are increasingly motivated by the falling cost of wind energy [5,6] and the substantial new capacity additions each year from the global wind industry [7].[1] To provide local planning authorities and regulators with robust information about the potential impacts and opportunities associated with these scenarios for their jurisdictions, high-spatial-resolution results from these scenarios are needed. Moreover, an appreciation for the inherent uncertainty and dynamic nature of the wind energy resource supply is increasingly critical to accurately characterizing the ability of wind energy to serve national and global electricity needs.

In the past, lower spatial resolution and static characterizations of wind energy potential were sufficient because the estimated resource was generally interpreted to be significantly greater than (Table 1) the anticipated commercial deployment of wind energy. Historically, primary constraints on wind energy market uptake were assumed to be economic or technical in nature with limited treatment of local spatial drivers [8,9]. Characterizing wind resource potential with higher spatial fidelity and eventually endogenous dynamic relationships could begin to illuminate possible future “saturation points” for wind energy and better inform how decisions that are made about siting, regulation, and technology development might influence those saturation points.

This work builds on and extends the literature in this field by applying several high spatial resolution datasets to the wind resource in conterminous United States (CONUS) and using scenarios or “siting regimes” to bound the uncertainty that results from the siting unknowns as well as the dynamic nature of wind energy potential. More specifically, our study design aims to explore the combined impacts of land access constraints, regulatory restrictions, and technology innovation. We capture 271 documented state regulations and county ordinances while using documented landscape-level siting constraints to identify additive spatial barriers and quantify the impacts on the U.S. wind power

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[1] 60 GW in 2019 for a cumulative total of 651 GW [7].

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Table 1
Summarizes these national and global wind technical potential studies.

Study	Wind Resource (spatial/temporal)	Land-Use Resolution	Land-Use Sensitivity	Wind Technology or Cost Sensitivity	U.S. Potential (TW)	Geographic Scope
[10]	38 km/1 h	500 m	Yes	Yes	51.4	Global
[11]	5 km[B]/1 h	1 km	No	No	9.8	Global
[12]	200 m/annual	30 m	No	No	10.4 (CONUS[A])	U.S.
[13]	200 m/annual	30 m	No	Yes	6.1[D] (CONUS[A])	U.S.
[14]	1 km	1 km	Yes	Yes	4.8[C,D]	Global
[15]	1 km[B]/1 h	300 m	No	No	8.5	Global
[16]	40 km/month-hour average	1 km	No	No	16.95 (CONUS[A])	Global

[A] Conterminous United States.
[B] NASA Modern-Era Retrospective analysis for Research and Applications wind resource data [17] that we downscaled using the Denmark Technical University "Global Wind Atlas" (Accessed October 12, 2020: https://globalwindatlas.info/).
[C] Reported generation potential only; generation is divided by the mean reported capacity factor to estimate capacity.
[D] Includes an economic threshold to limit wind resource.

supply curve. Our analysis incorporates three wind turbine technology characterizations and costs to represent current and future turbines. We compare the trade-offs between turbine sizing and technical potential, where larger tip heights reduce the developable capacity (because of setback requirements) but enable greater electrical energy production. Finally, we explore national infrastructure setback distances as a function of turbine size and how they might affect available capacity and generation potential. Our objective is to combine these factors in a scenario framework to evaluate the range of supply curve outcomes and provide a comprehensive assessment of the U.S. wind energy potential.

Our study builds on the advancements and findings reported in the recent literature, which has demonstrated the need for higher-resolution wind resource and built environment data to better capture localized resource variability and land availability. Chu and Hawkes [15] merged satellite-based land use and land cover data with Open Street Map–a vector crowd-source database–in an effort to improve representation of local features. Bosch, Staffell, and Hawkes [11] developed downscaling methods to better capture the spatial variability of the wind resource. Kiesecker et al. [18] explored wind potential by evaluating only previously disturbed lands.

The literature has also demonstrated creative and effective macrolevel proxies for representing complex local siting issues. Tegen et al. [19] explored wind potential reductions as a function of wildlife siting sensitivities and potential radar interference. Wu et al. [20] systematically explored varying degrees of siting constraints focused on protecting sensitive wildlife and landscapes for the western United States. Silva Herran et al. [14] explored wind potential in proximity to urban areas as a proxy for social acceptance and transmission minimization. Brown et al. [13] introduced a new methodology in which they evaluated wind potential using a levelized avoided cost of energy to identify thresholds for wind technical potential. In a more in-depth study of the sensitivity of wind potential, Rinne et al. [21] evaluated land use and turbine technology scenarios in addition to cost sensitivities to better bound near-term wind economic potential.

Though the literature on wind potential is ample, it has been primarily about global and European-focused assessments [15,11,14,10,16,22,23], where higher spatial resolutions have been applied [21,24–26]. There have also been subnational or state-specific detailed wind potential studies in the United States [20,27], but limited assessments have been undertaken with a focus on the full CONUS [13,12]. With the present work, we intend to add to this rich literature with a focus on the CONUS.

2. Methodology

2.1. Methods overview

Wind potential is often assessed in terms of geographic (or resource), technical, and economic potential [13,21,12,28,29]. Each type of measure represents a succession of additional complexity and input assumptions that leverage similar data and a common analysis flow. Ultimately, this results in a characterization of the developable quantity, quality, and cost of wind resources that can be sorted to represent a supply curve. Though there is some agreement in the literature about the broad definitions of wind potential, studies will often incorporate slight variations to an analysis or apply macrolevel proxies to illuminate particular challenges to wind energy deployment. In this section, we describe our approach for modeling wind power potential for the CONUS. We first introduce the techno-economic modeling framework we use to create our wind potential estimates [30]. We proceed by describing our spatially explicit representation of siting constraints (i.e., exclusions). We then introduce siting regimes, or collections of siting constraints and our turbine design and cost assumptions.

2.2. reV modeling

The Renewable Energy Potential (reV) model [31] can be used to conduct detailed assessments of renewable energy resources, technology performance, and plant costs while considering the geospatial intersection of grid infrastructure and location-dependent siting considerations; see Supplemental Information (SI) for the analysis flow in reV. The reV model operates at several spatial resolutions. Land use and land cover data are represented at 90 m (m). Where more-spatially refined data exist, the percentage of occupied land of each 90-m grid-cell is quantified to represent the area available for installation of wind turbines. The wind resource spatial resolution is 2 kilometers (km). Wind resource in reV is represented by NREL's WIND Toolkit [32], which comprises seven years (2007–2013) of hourly modeled meteorological data at several hub heights.[2] Discrete wind plant sites are represented at 11.5 km, which results in 67,000 individual wind sites across the CONUS. The available capacity in each site can be reduced by excluded land area, and each site captures the unique techno-economic characteristics as driven by the wind resource and distance to transmission.

To better account for turbine siting constraints, we directly link

[2] The WIND Toolkit has wind speeds at 10-, 40-, 60-, 80-, 100-, 120-, 140-, 160-, and 200-m heights. Where wind speed heights do not match the turbine hub height, reV dynamically adjusts wind speed to match hub height using a power law exponent.

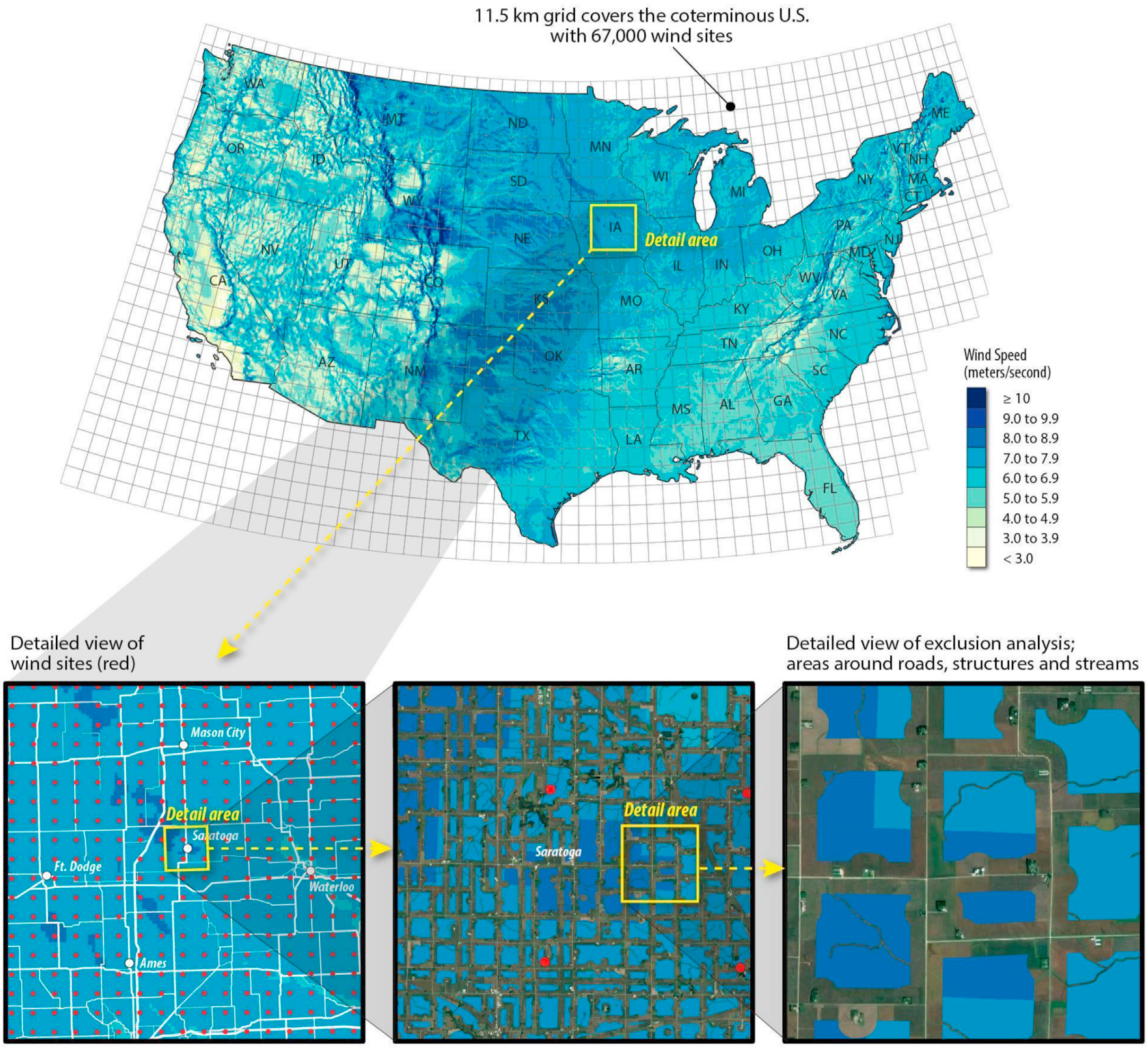

Fig. 1. The geographic scope and local spatial resolution used to estimate wind supply curves.

infrastructure setbacks to turbine tip heights based on documented siting ordinances (described in Section 2.3). Height ordinances are also applied where applicable. Fig. 1 illustrates the spatial fidelity of our siting considerations, which include individual roads, buildings, and other built infrastructure. The reV model also estimates hourly plant generation using the Systems Advisor Model [33] over seven years to reduce biases of interannual variability. Plant economics are then used to allocate grid connection costs as a levelized cost of transmission, which are based on a ranking by levelized cost of energy (LCOE) [30].

2.3. Siting Constraint Components

Siting considerations for wind projects include competing land use and associated infrastructure, site topography, siting ordinances, and protected areas.[3] Collectively, these factors affect development suitability and are important for understanding cumulative wind resource potential along with its cost and performance characteristics. Siting considerations impose spatial constraints that a wind project developer might face when prospecting for new plant locations or siting individual turbines. In simple terms, spatial exclusions either identify land already occupied by another physical feature or represent possible challenges associated with social, ecological, and wildlife considerations [34–42], or legal or jurisdictional restrictions that would impede development of a wind plant or placement of a turbine.

Here we compile localized regulatory information and use high-resolution data to capture those processes and features that are critical to land development potential. In doing so, we overcome common challenges with ensuring adequate spatial representation over broad geographic extent. Next, we detail these spatial exclusions using three thematic categories: infrastructure, regulatory constraints, and physical variables.

2.3.1. Infrastructure

Land use and land cover data, such as the National Land Cover Dataset [43], are commonly used to represent the extent of various human uses and dominant biophysical cover. Despite their

[3] We do not evaluate wildlife-specific siting considerations outside protected land status exclusions.

widespread use across diverse applications, land use and land cover data may be overly generalized for specific applications like wind siting that require higher-fidelity spatial information and increased thematic detail to differentiate, for example, between completely undeveloped areas and low-density settings characterized by dispersed structures. Where possible, our guiding approach is to use high-resolution vector data to represent linear and other small-scale features. To supplement the high-resolution features, we incorporate the Global Human Settlement Model [44] to capture high-density urban development. We also incorporate airport extents from the Homeland Security Infrastructure Program Gold [45].

2.4. Building footprints

To represent the presence of structures that could require setbacks for wind development, we use Microsoft building footprints, a vector spatial database of every building footprint (~124 million) in the United States [46] USBuildingFootprints n.d..

2.5. Roads

For high-quality representation of roads, we integrate the HERE Technologies vector roads within the Homeland Infrastructure Foundation-Level Data (HIFLD) [47]. HERE Technologies roads are used in routing algorithms, assisted, and autonomous vehicle applications, and are thus accurate and detailed. We use the lane count information provided in the data, and we assume width per lane of 3.6 m to represent the spatial dimensions.[4]

2.6. Railroads

Railroads traverse 417,430 km across the CONUS. We integrate the HIFLD railroads vector spatial database. We approximate rail widths, including subgrade, using aerial imagery. We assume 15 m represents the width of a typical rail line, which accounts for lines to include multiple rail ties.

2.7. Electric transmission rights-of-way

We also consider electric transmission lines as another infrastructure that could reduce the land available for wind deployment. We consider 875,728 km of transmission lines with voltage ratings equal to or greater than 69 kV from the HIFLD. To estimate excluded areas associated with these lines, we assume rights-of-way that vary with the voltage rating using recommendations from National Grid and Duke Energy (see SI).

2.8. Radar

Radar exclusion zones, which are typically a set distance away from the radar tower and based on rules of thumb, are often incorporated into wind potential estimates [19]; this is because turbines can adversely interact with radar systems. To capture additional detail, we incorporate "line-of-sight" for NEXRAD, short range radar (SRR), and long range radar (LRR), which take topographic effects into account when modeling a radar viewshed.[5] Though radar adds additional siting complexity, turbines can still be sited in proximity to radar using sophisticated tools.[6] We incorporate this additional radar dataset to quantify the magnitude of wind resource that could potentially require sophisticated radar tools for siting or operational constraints to minimize radar interference.

2.8.1. Regulatory constraints

Siting ordinances refer to county or state regulations that guide the development of wind power. They often include rules about sound, shadow flicker, hub height, property values, wildlife impacts, and setbacks. We reviewed various sources and created a dataset of documented state and county wind ordinances; it is current as of 2019 and includes 271 county and 7 state ordinances that pertain to hub height and setback requirements for buildings, roads, rail, transmission, and rivers [48].[7] Using the ordinance database, we incorporate spatial setbacks for our selected turbines (discussed in Section 2.5) as a function of maximum tip height to evaluate the trade-offs between taller turbines and larger setbacks.

Protected lands are identified in the Protected Areas Database of the United States [49], which contains spatial boundaries of lands that are managed for biodiversity, natural, recreational, and cultural uses. To supplement these data, we incorporate boundaries of several federal land designations that protect cultural and ecological landscapes. We also include the data from the National Conservation Easement Database,[8] which captures public and private conservation easements. See SI for a full list of spatial datasets included.

2.8.2. Physical variables

We include several other siting constraints that capture landscape-level (large-area) siting considerations, including terrain slope and elevation data derived from the NASA Shuttle Radar Topography Mission (90-m spatial resolution) [50] and mountainous physiographic regional classifications derived from global Hammond landforms [51] (details in SI). Moreover, we exclude lands identified as water bodies or wetlands in the National Land Cover Dataset.

2.9. Siting regimes

We develop three main siting regimes, each of which represents a collection of individual siting constraints, to reflect plausible differences in wind siting restrictions. We also create the siting regimes to capture a range of deployment barriers, in effect bracketing estimates of wind potential along a theoretical gradient of siting restrictiveness. However, we do not analyze the probability of any siting regime, and they are not intended to describe likely future expectations. The siting considerations applied within each siting regime are not mutually exclusive (e.g., many buildings and roads are within excluded urban areas). For each siting regime, we apply a similar philosophy and, therefore, a consistent level of restrictiveness for all siting considerations. Overviews of the siting regimes are presented in this section, and specific assumptions are detailed in Table 2 and SI.

Open Access is the least restrictive siting regime. It applies physical barriers to wind development, including water bodies, buildings, and roads, and it restricts development on legally protected lands (e.g., national parks, national wilderness areas, and

[4] Recommended highway widths from the Federal Highway Administration, https://highways.dot.gov/.

[5] Line-of-sight viewsheds are calculated assuming 500 foot above ground level.

[6] "Radar and Airspace," American Wind Energy Association (AWEA), Accessed June 12, 2020: https://www.awea.org/policy-and-issues/project-development/radar-and-airspace.

[7] Details available in SI. We do not include property boundary setbacks, as they generally require knowing which properties are participating in a wind project.

[8] National Conservation Easement Database, https://www.conservationeasement.us/.

Table 2
Overview of exclusions applied to the three siting regimes. Details of spatial layers are in SI.[a] Where overlaps exist, documented ordinances are used.

Siting Exclusion Category	Open Access Scenario	Reference Access Scenario	Limited Access Scenario
Infrastructure			
Setbacks to transmission rights-of-way, railroads, roads, building structures[a]	Structure only, no setback	Setback = 1.1x wind turbine tip height	Setback = 3x wind turbine tip height
Urban areas and airports	Excluded	Excluded	Excluded
Radar	–	4-km NEXRAD, 9-km SRR/LRR	NEXRAD and SRR/LRR line-of-sight
Regulatory			
Documented state and county setback and height ordinances[a]	–	Applied	Applied
Protected public lands and conservation easements	Excluded	Excluded	Excluded
Other federal lands	–	–	Excluded
Physical			
Slope >25%	–	Excluded	Excluded
Mountainous landforms and high (>9000 ft) elevation	Excluded	Excluded	Excluded
Water and wetlands (with 305-m buffer)	Excluded	Excluded	Excluded

national wildlife refuges). In addition, it restricts development on lands associated with conservation easements. The Open Access scenario sets a ceiling for wind potential and is used as the base set of spatial exclusions for the Reference Access and Limited Access scenarios.

Reference Access is a regime that balances siting considerations and is informed by common practices to guide development. For example, a 25% slope restriction is used to prevent erosion [52] in addition to other physical restrictions that are assumed under the Open Access scenario. The Reference Access scenario also applies 7 documented state and 271 county setback and height restrictions. For regions without setback requirements, we apply a typical county ordinance minimum setback of 1.1x the maximum turbine tip height from infrastructure for safety reasons.[9] We also assume buffered setbacks from radar stations (4 km and 9 km for NEXRAD and SRR/LRR respectively), as established by Tegan et al. [19].

Limited Access is a combination of the more stringent siting considerations. For example, in addition to all the exclusions used for Reference Access, Limited Access applies a greater setback requirement from buildings and civil infrastructure, excludes any development within radar line-of-sight, and excludes all federal lands.[10] Of these, the 3x turbine tip height setback requirement to infrastructure is the most significant, and it represents a combination of factors, including social opposition to wind development near infrastructure and residences. In the highest turbine tip height case (the Advanced technology case, which is described in Section 2.5) the 3x setback is equivalent to 705 m. For context, 21 U S. counties (of 271 counties documented here) have a setback greater than or equal to 3x or 705 m. Many European regions have a 1-km setback [53]. These comparisons show a future in which some of the most restrictive siting requirements present today are applied throughout all U.S. regions, thereby limiting access for wind development.

2.10. Wind turbine details

Estimating wind potential requires assumptions about turbine characteristics, including rated capacity, rotor diameter, hub height, and power curve. These design parameters along with an assumption about power density (as a function of turbine spacing) are used to determine how much energy can be produced given the wind resource and available land area.

Rapidly evolving turbine designs are resulting in higher hub heights and larger rotor diameters [5]. To capture the effects of these advancements, we consider three turbine design cases in our analysis. For each design scenario modeled, we apply the same turbine in all locations rather than optimizing the turbine choice by region. This scenario approach enables us to isolate the effects of turbine technology advancements.

In the wind potential literature, available land area is used to determine capacity potential by using a power density assumption, which is represented as MW/km^2. Power density is typically determined through empirical studies of existing wind plants [54] or by using a rotor diameter spacing assumption [21]. In our analysis, we use a constant 3 MW/km^2 for all wind turbine designs. Applying the reV wind site resolution of 11.5 km results in a maximum capacity potential of 397 MW per site. We do this for two main reasons. First, wind turbine design is rapidly evolving and is changing wind plant power densities [55]. And second, rotor diameter spacing–using our turbine designs–results in roughly the same power density.

Our wind assumptions are derived from the 2019 Annual Technology Baseline 2019 (ATB) [56] -a technology-specific database with cost and performance parameters across a range of R&D advancements scenarios. Assumptions include the turbine configurations (power rating, rotor diameter, hub height) and costs (capital expenditures and operational expenditures). For onshore wind, we consider the Moderate and Advanced technology innovation cases from the ATB. These cases are projections of the cost and characteristics of turbines in 2030. In addition, we compare with a 2018 market average turbine from Stehly and Beiter [57]; which we refer to as the Current technology case. Table 3 details our turbine design cases and costs assumptions. To represent the regional variability of capital costs (e.g., regional variability in labor rates, cost of land, and taxes), we use regional multipliers (see SI).

The reV framework estimates the cost of building transmission for each wind power plant in its supply curve model using user-defined cost assumptions. We assume a cost of $2416/MW-km ($2018) to build a spur-transmission line and $14,848/MW to create a point of interconnection. These represent inflation adjusted costs used by Cole et al. [3].

3. Results

In this section, we present wind supply curve results and their variations across siting regimes (Section 3.1) and wind technology (Section 3.2).

For the *siting regime dimension*, we compare the Open Access, Reference Access, and Limited Access wind supply curves based on the exclusion assumptions presented in Section 2.4. In these

[9] "Setbacks," American Wind Energy Association (AWEA), Accessed June 11, 2020: https://www.awea.org/policy-and-issues/project-development/state-and-local-permitting/setbacks.
[10] We do not exclude tribal land in any of the siting regimes, as wind development currently exists on tribal lands, particularly in Oklahoma.

Table 3
Turbine design and cost variables.

Turbine Characteristic	Current Case (2018 Market Average)	ATB Moderate Case	ATB Advanced Case
Turbine rating (MW)	2.4	5.5	7
Rotor diameter (m)	116	175	200
Hub height (m)	88	120	135
Specific power (W/m2)	227	229	223
Max tip height (m)	146	208	235
Capital expenditures ($2018/kW)	$1433	$1161	$861
Fixed operation and maintenance ($2018/kW)	$45	$39	$34
Losses (%)	16.70%	11.80%	9.40%
Power density (MW/km^2)	3	3	3

Table 4
Scenario matrix representing unique combinations of siting regimes and turbine designs modeled.

	Open Access Scenario	Reference Access Scenario	Limited Access Scenario
Current Case	–	x	–
Moderate Case	x	x	x
Advanced Case	–	x	–

scenarios, we hold the turbine technology constant (using Moderate case technology).

Across the *wind technology dimension*, we hold the siting regime constant (Reference Access) but vary the assumed wind design based on the configurations described in Section 2.5. These include the 2018 (Current), 2030 Moderate, and 2030 Advanced case designs.

Our scenario matrix is presented in Table 4.

The primary metrics we evaluate include the technical potential of onshore wind in capacity terms, the cost and performance characteristics of the developable potential, and grid interconnection cost estimates. Results are presented for the CONUS as a whole and by region, including at the underlying 11.5-km wind site resolution and at a broader aggregate regional level shown in Fig. 2.

3.1. *The impact of siting regimes on wind supply curves*

3.1.1. *Wind capacity potential and wind site intensity*

The area of the CONUS is 7,810,878 km^2,[11] which if it were fully developable would equate to a *wind resource potential* of 23,432 GW assuming a power density of 3 MW/km^2. Obviously, not all areas are suitable for wind development.

Under the Open Access scenario, we assess a more realistic upper bound to the wind potential by excluding locations where development is highly unlikely or is precluded because of existing infrastructure or laws. Altogether, the aggregate of these exclusions cover 2.7 million km^2 in land area (Fig. 3). This results in a resource potential of 15,175 GW or 65% of the potential when *all* land is considered.

In the Reference Access scenario, exclusions amount to 5.2 million km^2 of aggregate land area. This amounts to a reduction of resource potential to 7827 GW or 52% of the potential from Open Access and 33% of all land.

Under the Limited Access scenario, we assess wind potential by applying stringent siting exclusions. These exclusions amount to 7.05 million km^2 of aggregate land area. All told, these considerations reduce the wind potential to 2280 GW, or 15% of the potential under the Open Access scenario and 10% of all land.

As seen in Fig. 3, road and building setbacks are the largest individual exclusions in the Reference Access and Limited Access scenarios. However, there is spatial overlap among all exclusions that when accounted for, reduce the aggregate land area. This is most apparent in the Limited Access scenario, which has a reduction of 9.65 million km^2 spatially overlapping exclusions are considered.

National reductions in potential can be visualized through capacity intensity maps (Fig. 4). Capacity intensity refers to the capacity available at an individual wind site as it is influenced by local spatial exclusions. The dark blue colors include sites with resource potential close or equal to the maximum available capacity for a wind site (397 MW).

In the Reference Access scenario, we see a reduction in capacity intensity (compared to Open Access) across the country except for along the Mountain and Great Plains regions and in other sparsely populated regions. In the eastern United States, lower capacities are a result of setbacks and dense infrastructure. In the West, slope restrictions further reduce capacity. The fully excluded counties in southern California are due to their mandated maximum turbine hub-height of 80 m, which is lower than any of our turbine technologies. For four California counties (Kern, Marin, San Bernardino, and San Diego), the 80-m maximum hub height results in a reduction of up to 165 GW of wind capacity potential (although setbacks introduced in the Reference Access scenario would have likely resulted in significant reductions given southern California's dense population).

In the Limited Access scenario, high-capacity sites are found in the least-populated locations along the seams of the three asynchronous interconnections in the CONUS power system, which are coincidentally colocated with high-quality wind resources. High-capacity sites are also present in the southwestern states of Arizona and New Mexico, where population densities are lower. In addition, pockets of high-capacity sites in New York, Maine, eastern Washington, and eastern Oregon are primarily a result of remote forested areas with low populations.

Fig. 5 shows the median and interquartile range in wind site capacity intensity across the three siting regimes to further illustrate the influences local siting considerations have on wind potential. Open Access has the largest mean wind site size of 260 MW, followed by Reference Access at 137 MW, and Limited Access at 48 MW. These results indicate that increasing siting constraints could result in lower density wind sites and more geographically dispersed wind development [20,58].

Siting regimes impact the available capacity in each region

[11] This includes all land and water except the Great Lakes.

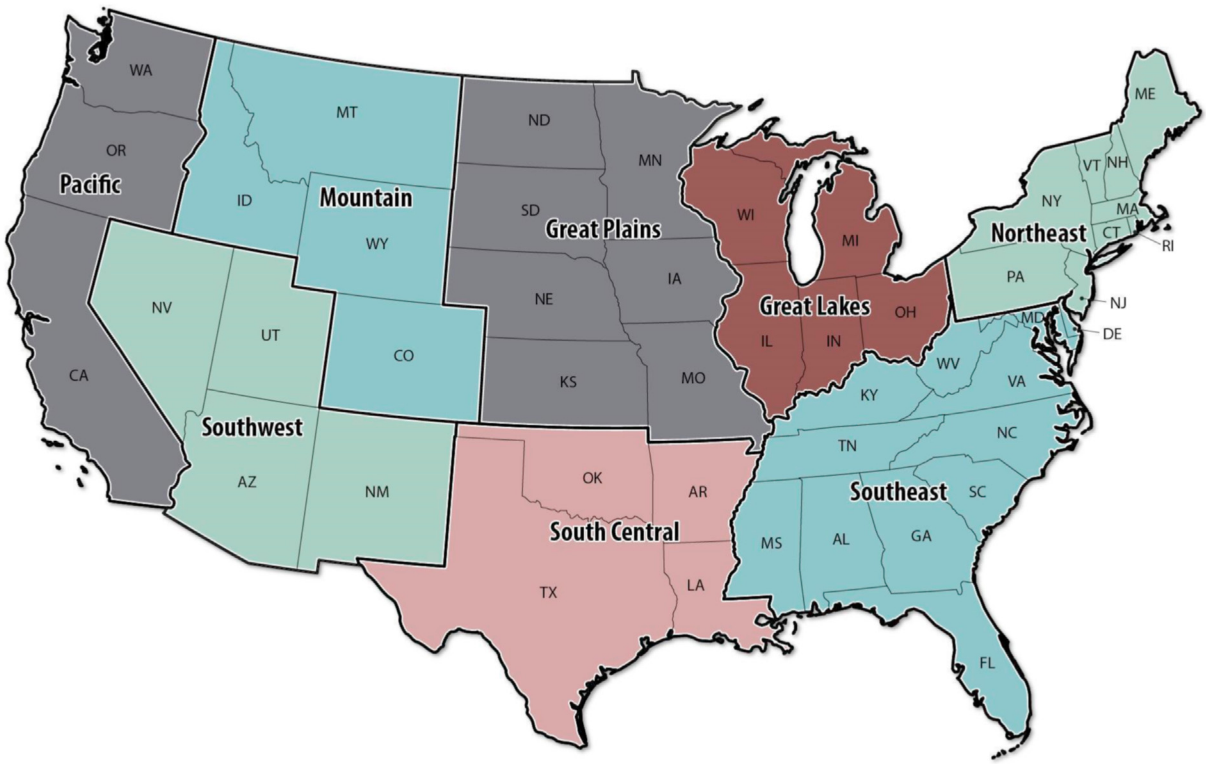

Fig. 2. Report regions of the coterminous United States.

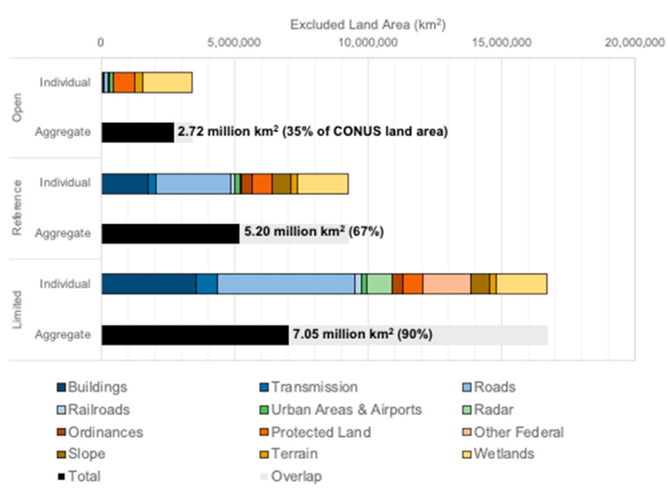

Fig. 3. The amount of land for individual exclusions applied to each siting regime. The aggregate bars quantify the total amount of land excluded in each regime after accounting for spatial overlap among individual exclusions.

differently, as presented in Table 5. For example, the Great Lakes, Pacific, and Southeast regions see a decrease in the relative share of capacity from Open Access to Reference Access to Limited Access scenarios, while the percentage share of capacity increases substantially in the Mountain and Southwest regions. Meanwhile, the other regions (Northeast, South Central, and Great Plains) retain a similar share of the national capacity regardless of siting constraint severity. These differences are in part driven by the amount of infrastructure on the landscape (i.e., density of road, rail, and transmission networks) and the density of structures. The regional capacity differences across these different siting regimes also suggest setback restrictions impact heavily populated regions (Great Lakes, Pacific, Northeast, and Southeast) more than less-developed regions (Mountain and Southwest).

3.1.2. Wind resource availability and quality

Thus far, we have presented results only in terms of the remaining total developable capacity after exclusions are applied. However, wind resource quality varies spatially, and understanding how siting regimes spatially intersect is crucial for evaluating the economic viability of wind projects. We found increasing siting restrictions (e.g., going from the Open Access to the Limited Access scenarios) reduces capacity for all wind speed ranges. In fact, for the CONUS resource as a whole, the *distribution* of available resource across wind speed bins is very similar between the three siting regimes (see SI). However, as seen in Fig. 6, impacts are not uniform across regions. Of most interest are impacts of siting restrictions on the highest wind speed locations. For example, for the developable capacity with an average wind speed >8 m/s in the Limited Access scenario, over 500 GW of capacity remains available. However, this is concentrated in the Great Plains, Mountain, and South Central regions. In the more heavily populated regions of the Northeast, Pacific, Great Lakes, and Southeast, less than 22 GW of combined capacity is available.

3.1.3. Implications for transmission interconnection costs

The site-dependent nature of wind energy also means transmission is required to deliver its energy to the electric grid. Evaluating the cost competitiveness of different wind sites requires considering transmission interconnection costs along with wind plant costs and performance characteristics across sites. To do this, the reV model evaluates the cost of transmission interconnection on a levelized basis considering the distance a spur-transmission would have to travel and the cost of the point-of-interconnection.

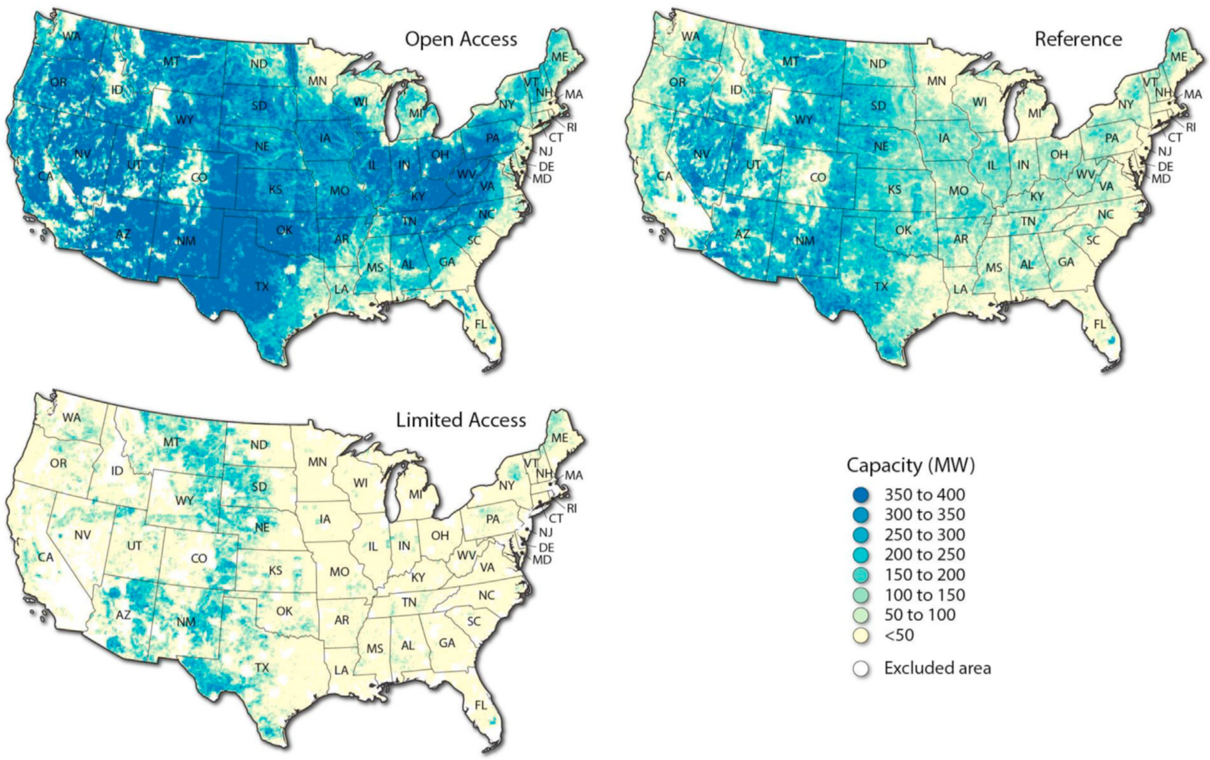

Fig. 4. Capacity intensity maps for the Open Access, Reference Access, and Limited Access scenarios.

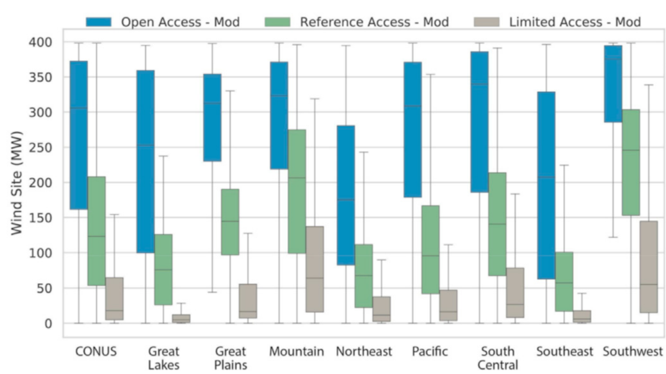

Fig. 5. Range of wind site size (capacity intensity) for each siting regime. Mod: Moderate case.

The reV model does not evaluate bulk transmission upgrade or expansion requirements.

For CONUS, we found that the mean levelized cost of transmission interconnection (LCOT) was lower for the more restrictive scenarios and is sensitive to wind site size. National LCOTs of $4.09/MWh, $2.96/MWh, and $1.55/MWh were observed for the Open Access, Reference Access, and Limited Access scenarios respectively. However, variability between regions is substantial, with LCOTs approaching or exceeding $10/MWh in a significant share of wind sites (Fig. 7). Across this full range, the results are consistent with recent findings by Gorman, Mills, and Wiser [59]; who found empirically that wind LCOTs ranged between $0.9/MWh and $11.2/MWh and had a capacity weighted average of $5.4/MWh.

Lower LCOTs represented in the more restrictive scenarios result from reV competing each wind site against one another for access

Table 5
Siting regime capacity results. The "% of total" column is calculated for each scenario to provide each scenario's regional share of capacity. Impacts of siting regimes for each region can be interpreted by comparing values across rows.

	All Land		Open Access Scenario		Reference Access Scenario		Limited Access Scenario	
Region	GW	% of Total	GW	% of Total	GW	% of Total	GW	% of Total
Great Lakes	1926	8%	1141	7%	391	5%	44	2%
Great Plains	4026	17%	2791	18%	1462	19%	403	18%
Mountain	3360	14%	2244	15%	1497	19%	548	24%
Northeast	1295	6%	629	4%	243	3%	76	3%
Pacific	2503	11%	1624	11%	611	8%	129	6%
South Central	3366	15%	2371	16%	1236	16%	432	19%
Southeast	3512	15%	1750	12%	557	7%	94	4%
Southwest	3349	14%	2622	17%	1827	23%	559	24%
Total	23,337	100%	15,175	100%	7827	100%	2280	100%

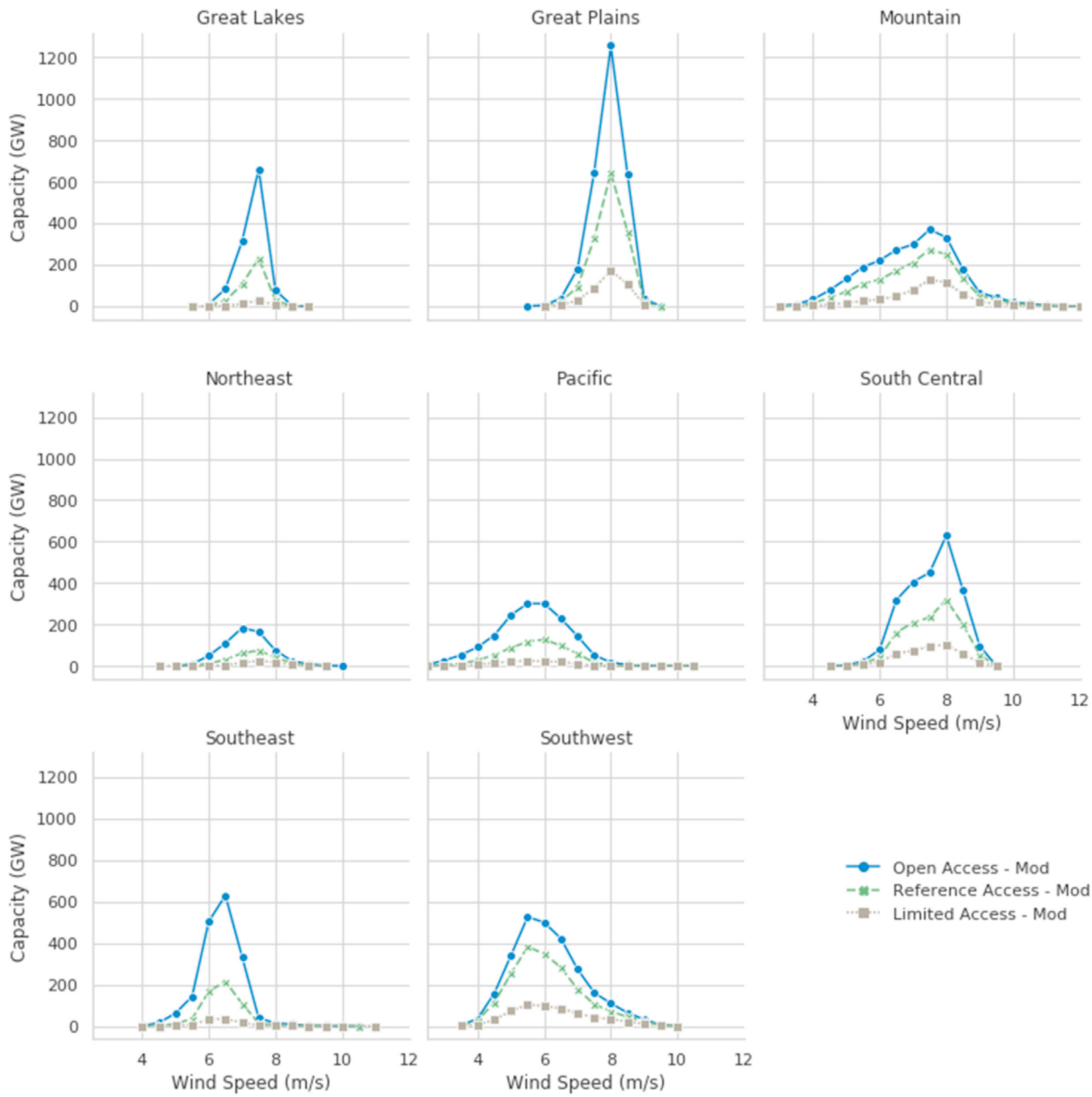

Fig. 6. Regional wind speed and capacity distributions for the three siting regimes.

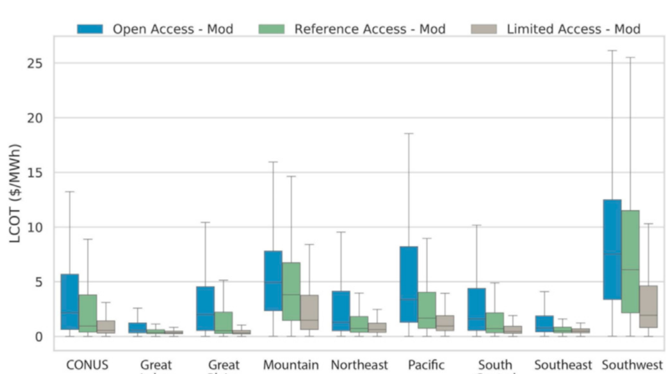

Fig. 7. Regional levelized cost of transmission for the three siting regimes.

to the electric grid and giving preference to the lowest-cost resource. In scenarios where there is less potential capacity (e.g., Limited Access), there is less competition, which results in lower mean transmission costs, as reported by reV. Notably, however, the lowest-cost 500 GW of capacity in the Reference Access and Open Access scenarios have mean LCOTs ($0.43/MWh and $0.54/MWh respectively) that are higher to those seen in the Limited Access scenario ($0.42/MWh), which suggests the observed differences in mean LCOTs may not be indicative of the differences in mean LCOTs for sites that might be selected from any one of the three siting regimes for future development. Moreover, modeled wind deployment under scenarios with greater siting restrictions have been found to lead to higher system costs from bulk transmission upgrade and expansion expenditures [58,60]; that are due to the distributed nature of wind deployment that tends to result when siting regimes are more limited. Such costs, which would be in addition to the LCOTs reported here, are not considered in the present analysis, as bulk transmission upgrades and broader interregional transmission expansion could be used to deliver electricity from a wide range of resources or multiple wind sites and therefore should not be fully attributed to an individual wind site. Such costs might also vary depending on future changes to the grid, which is outside the scope of our analysis.

3.1.4. Implications for levelized cost of energy

Levelized cost of energy (LCOE) in this report represents the combination of the site-LCOE and the LCOT. Site-LCOE refers to the cost to develop a particular wind site location given the capital and operational expenditures in addition to financing assumptions but without considering any transmission costs (equations found in SI). LCOT is described in Section 3.1.3. The siting regime scenarios explored here assume the turbine cost and configurations of the Moderate cases, which represents a possible advancement in wind design in the year 2030. Nationally, we found there is substantially less low-cost capacity (433 GW < $30/MWh) in the Limited Access scenario than in the Reference Access scenario (1369 GW < $30/MWh) and Open Access scenario (2000 GW < $30/MWh).[12]

Fig. 8 shows the distribution of LCOE for the three siting regimes. And siting considerations clearly play a role in shaping the regional spatial distributions of LCOEs. The Great Plains, South Central, and Mountain regions make up 50%, 35%, and 8%, respectively, of the resource available below $30/MWh in the Reference Access scenario. Given the projected turbine technology advancements in the Moderate case, we see the Southeast (4 GW) and the Northeast (2 GW) regions with less than $30/MWh of capacity, again in the Reference Access scenario.

3.2. Implications for advancing technology on wind supply curves

In Section 3.1, we focus on the difference in the wind supply curve across siting regimes while keeping technology assumptions constant (based on the 2030 Moderate technology case assumptions). In this section, we examine the effects of turbine advancement while keeping the siting regime constant (Reference Access). We present three cases that capture a range of technology advancements, and we examine their cost and supply implications. As described in Section 2.5, we assume the same power density (3 MW/km^2) in all scenarios, including scenarios with different turbine assumptions. However, because setbacks–from documented ordinances and our assumed ones where no regulations exist–are based on turbine tip heights (1.1x in the Reference Access scenario), the technology assumption affects the developable potential. Tip heights in the Current, Moderate, and Advanced cases are 146 m, 208 m, and 235 m respectively. In the Current technology case, there is 9124 GW of wind capacity potential. After accounting for these tip height differences and the associated setback requirements, we find a 14% (7827 GW) and a 20% (7330 GW) decrease in wind capacity potential across the CONUS in the Moderate and Advanced cases compared to the Current case.

Although larger turbines result in lower capacity potential because of increased setback distances, they also can produce more electrical energy per unit of capacity (i.e., they have higher capacity factors). In this instance, the increased capacity factors are the result of the higher hub heights that these technologies rely on as the specific power of these turbines is not significantly different between the Current and Advanced cases. As a result, differences in wind resource potential in terms of *generation* between the three technology cases are proportionally smaller than the differences in available capacity. In fact, for the turbines applied here, we find a difference of less than 1% in generation potential (Current: 24,774 TWh; Moderate: 24,679 TWh; and Advanced: 24,573 TWh) for the CONUS as a whole (Fig. 9).

Differences in capacity factor impact LCOE as well. Using the capital and operational expenditure assumptions from the ATB (see Section 2.5), we observe that adoption of more advanced turbines can lead to reductions in LCOE in all regions (Fig. 10). With Moderate technology case advancements, we estimate that 1369 GW (5,731,327 GWh) of deployable capacity has an LCOE below $30/MWh by 2030 while no resource is below this threshold for the Current (2018) case. For the Advanced case, we estimate 3892 GW (15,725,807 GWh) of wind would have an LCOE less than $30/MWh and even 219 GW would be below $20/MWh (1,030,857 GWh).

Though the advancement of technology has limited impacts on the national generation potential, impacts vary regionally and depend on differences in wind speed and wind resource at the various hub heights we consider [61]. More specifically, in locations with modest wind power capacity potential impacts and higher wind shear,[13] one could reasonably expect that the energy generation gain of moving to higher hub heights could offset the reductions in wind capacity potential that occur there; and this is essentially what we found in the Great Lakes, for both the Moderate and Advanced technology cases. On the other hand, in regions with larger capacity potential reductions and lower levels of wind shear, one would expect to see the loss of capacity translate more into losses in energy generation potential as well; this is essentially what occurs in the Southwest and Mountain regions, particularly between the Current and Moderate cases. Although, even in these regions, the incremental lost capacity resulting from the shift between the Moderate and Advanced cases is to an extent that the additional hub height gain that accompanies the shift is sufficient to offset any additional lost energy and nearly match the energy generation potential resulting from Current case technology.

Of particular interest is that optimal turbine selection–from a simple regional energy generation perspective–varies depending on key spatial factors, including existing infrastructure, required setbacks, and expected wind shear. With that in mind, a critical caveat applies here–it has to do with the potential intra- and inter-wind plant wake effects that might also be impacted by the density of turbine placement that results when applying the different technology assumptions applied here. Aside from the sensitivity performed, these effects are outside the scope of the current analysis. Also relevant are (1) the plausibility of deploying wind energy at levels at or even approaching the potential estimated here and (2) a consideration for the spatial trade-offs associated with larger or smaller turbines when seeking a quantity of wind energy that ultimately falls significantly below the full potential calculated here.[14]

In terms of regional cost impacts from changing technology, the relatively static nature of transmission costs results in their becoming an increased share of the overall cost of wind as turbine technology advances and turbine costs are reduced (Fig. 11, bottom-row maps). More specifically, we find decreasing LCOEs from

[12] $30/MWh is approximately equal to the average energy price from restructured U.S. electricity markets in recent years [64].

[13] Wind shear refers to the difference in wind speed or direction over short distances in the atmosphere.

[14] Based on these observed differences between regions, future work could explore how differences in turbine rotor diameter or specific power–as opposed to primarily hub height, as is the case here–might further mitigate the potential for reduced energy generation resulting from reduced capacity potential. Such efforts might rely on more site-specific optimization of hub height and rotor diameter with dynamic consideration for siting and setback constraints. In locations where tip height increases substantially reduce capacity potential, it may be advantageous to expand rotor size rather than hub height.

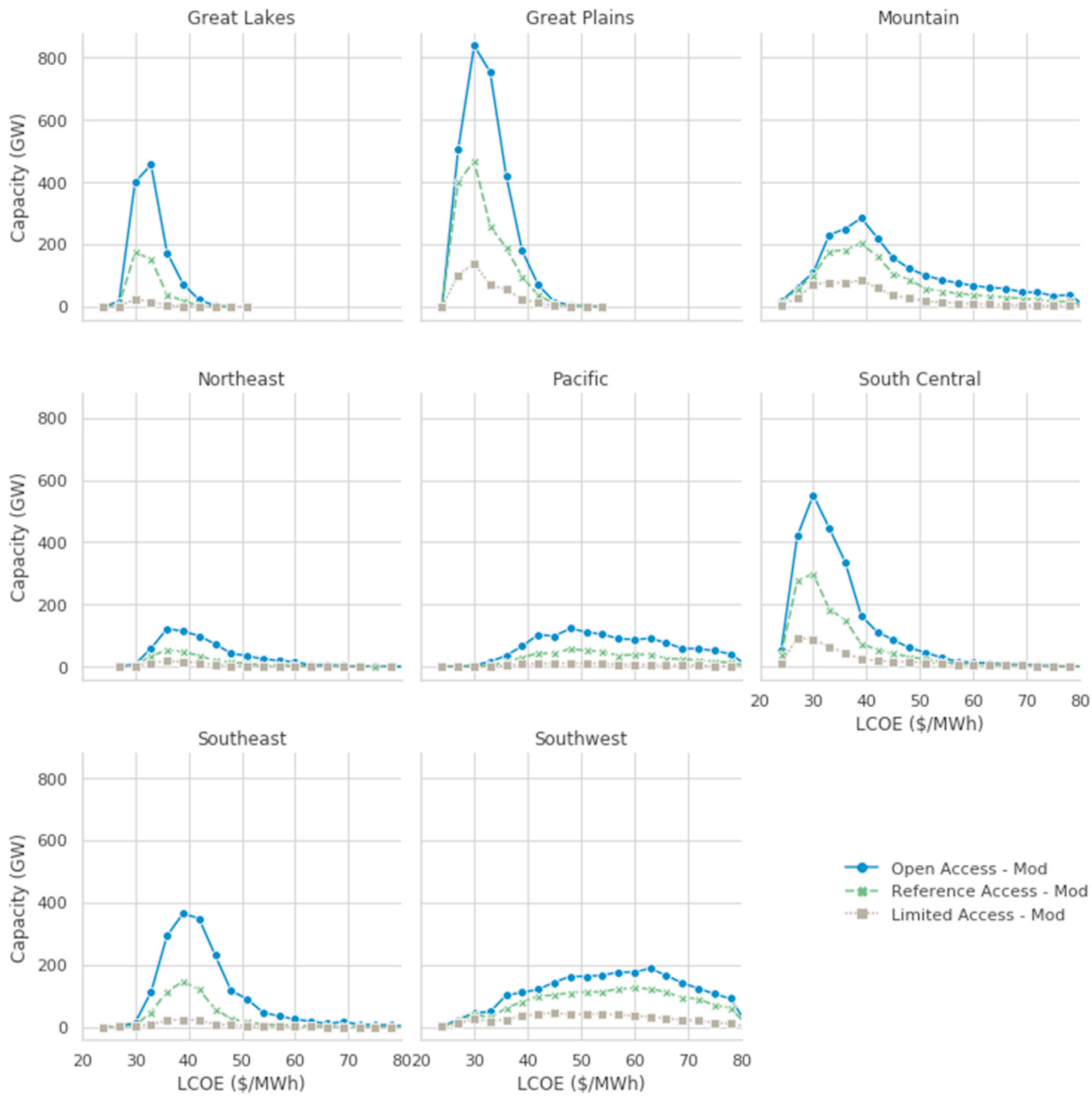

Fig. 8. Regional levelized cost of energy ($/MWh) in $3/MWh bins for the three siting regimes. LCOE (x-axis) is limited to $80/MWh to preserve the shape of the lower cost distribution.

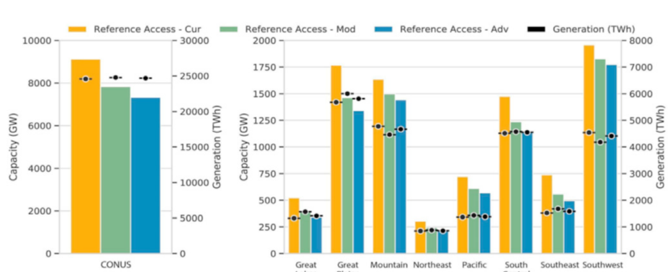

Fig. 9. Regional capacity and generation potential among the turbine technology cases. Cur: Current case; Mod: Moderate case; Adv: Advanced case.

technology advancement across all regions of the CONUS (top-row maps) starting from the Current to Moderate and then the Advanced technology cases. We also find that less transmission-dense portions of the western United States have proportionally larger transmission costs, which is a result of wind resources requiring longer spur-transmission lines to tap into the existing grid infrastructure and in some cases very low site-specific wind plant LCOEs.

4. Conclusion and discussion

Resource potential assessments underpin energy system planning. As clean energy ambitions have expanded, critically evaluating renewable energy supply has become an integral part of wind potential assessments. These assessments are complex because of the intersection of the numerous factors and multiple disciplines involved, including energy systems analysis, technology expertise, land use and ecology, social science, and policy.

We find a 7x difference in total U.S. wind technical potential across the three primary siting regimes studied. Of all the

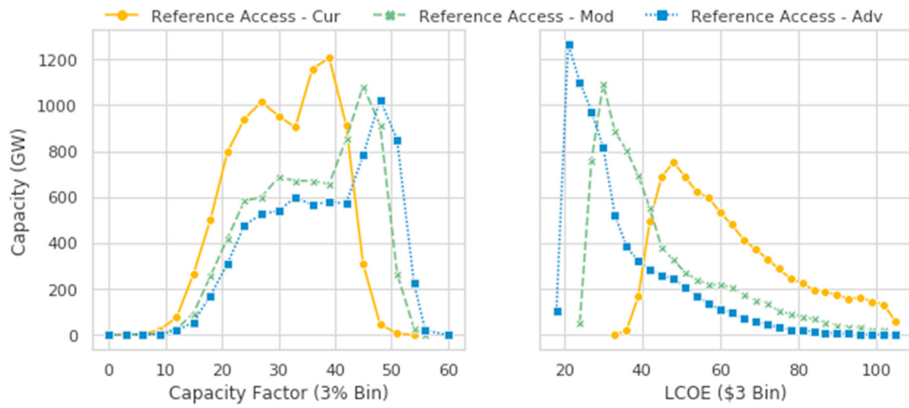

Fig. 10. National wind capacity by capacity factor and LCOE for three turbine technology cases. LCOE is limited to $100/MWh.

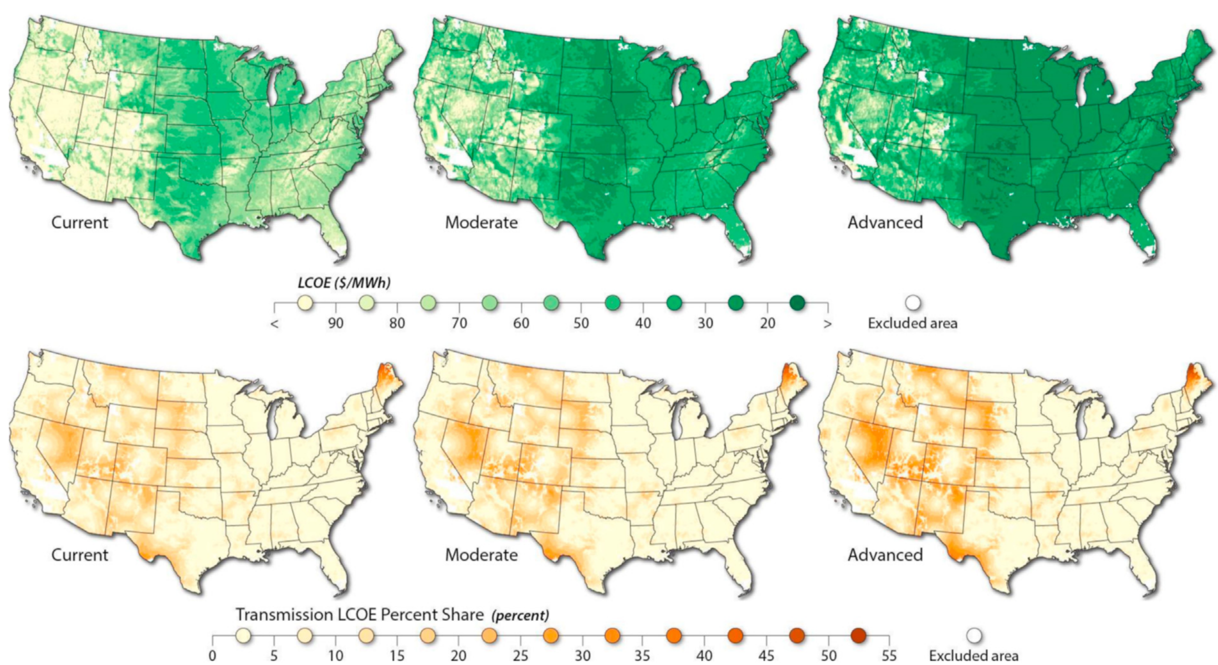

Fig. 11. Total LCOE (top row) and share of total LCOE from transmission interconnection (bottom row) across turbine technology cases.

exclusions analyzed, assumptions about infrastructure setbacks are found to have the largest impact on the technical potential. We find that, because setbacks are influenced by turbine tip heights, future wind technology evolution might negatively impact the technical potential in capacity (GW) terms, but because of the higher wind speeds at higher above ground levels and the greater energy capture potential with larger rotors, the wind generation potential is largely unaffected: the change in estimated annual energy production is less than 1%. Furthermore, we observe how siting considerations can dramatically impact wind *plant* sizes, particularly in more-populated regions where conflicts with the built environment can challenge the development of large-scale wind power plants. These trade-offs in wind turbine and plant design and their interactions with other land uses should be considered in local energy and land planning, and they deserve further study.

Despite the level of detail in our analysis, we identify several possible improvements and extensions. First, ecological, wildlife, noise, and visual factors are not considered in the analysis. Second, the analysis could be extended to other generation technologies (e.g., offshore wind, solar, and nuclear) and power system infrastructure (e.g., transmission) that also face siting uncertainties. Third, though the analysis examines developable *potential*, it does not examine the impacts of siting regimes or technology change on future electric sector investments and system evolution. A companion paper Mai et al. [58] uses the siting regimes introduced in the present analysis to examine how siting restrictions might impact future U.S. wind deployment and power system transitions.

Fourth, future methods development could move beyond single power density for all wind turbine designs and all sites and binary constraints based on the definitions of each siting regime. Empirical observations capture a range of power densities as a result of wind being deployed in an array of diverse landscapes . Moreover, Kitzing et al. [62] show that siting decisions are often impacted by negotiations between developers, landowners, and regulators. Fifth, existing energy deployment was not explicitly modeled as a spatial constraint, but large-scale energy facilities were captured in the structures database, albeit with detail missing for small features (e.g., well pads). Finally, our analysis does not endogenously consider changing attitudes about wind siting with wind penetration or interactions between wind power plants via wake effects and associated economic impacts [63], which may also substantially impact technical potential.

Notwithstanding these limitations, our analysis advances traditional wind technical potential assessments by using geospatial modeling and multidimensional datasets with unprecedented resolution, which can and should be compared to other global and subnational studies presented in Table 1. Based on our analysis, we find that wind has a technical potential of 7800 GW (24,679 TWh) in the CONUS, but under a more restrictive siting regime, this potential could decline to 2280 GW (7332 TWh). In either case, these estimates for wind far exceed current U.S. electricity needs; however, which regime is realized can impact the economic potential for wind along with power system costs as a whole and by region.

Author contributions

Anthony Lopez: Conceptualization, Writing – original draft, Funding acquisition. Trieu Mai: Conceptualization, Writing – review & editing, Data Visualization. Eric Lantz: Writing – review & editing, Funding acquisition. Dylan Harrison-Atlas: Writing – review & editing. Travis Williams: Geospatial Modeling and Execution. Galen Maclaurin: Writing – review & editing. Funding Acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.socscimed.2021.113766.

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