Exploring the Impact of Near-Term Innovations on the Technical Potential of Land-Based Wind Energy

Owen Roberts, Travis Williams, Anthony Lopez,
Galen Maclaurin, and Annika Eberle

National Renewable Energy Laboratory

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List of Acronyms

AEP	annual energy production
ATB	Annual Technology Baseline
BOS	balance-of-system
CapEx	capital expenditures
CONUS	contiguous United States
DOE	U.S. Department of Energy
FCR	fixed change rate
GE	General Electric
GW	gigawatt
IEC	International Electrotechnical Commission
km	kilometer
kW	kilowatt
LandBOSSE	Land-based Balance of System Systems Engineering [model]
LCOE	levelized cost of energy
LCOT	levelized cost of transmission
m/s	meter per second
MW	megawatt
MWh	megawatt-hour
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
OpEx	operational expenditures
R&D	research and development
reV	Renewable Energy Potential Model
SAM	System Advisor Model
TW	terawatt
W	watt
WIND Toolkit	Wind Integration National Dataset Toolkit

Executive Summary

Land-based wind energy may play a critical role in reaching emissions reductions goals and high renewable contribution scenarios, with estimates at or exceeding one terawatt of land-based wind energy by 2035 to reach 100% clean electricity (Denholm et al. 2022). Deployment at this magnitude may require significant investments in transmission infrastructure and will require significant land area for new wind turbines and transmission (Larson et al. 2021; Denholm et al. 2022; Gagnon et al. 2022). Cost reductions via technological advancements in wind turbine design, construction, and maintenance will have a major role in enabling the scale of deployment required. Since 1998, the levelized cost of wind energy has fallen by over 60% due to improvements in capacity factors, advancements in turbine controls, and cost reductions in installation, operation, and maintenance (Wiser et al. 2021). These cost reduction pathways, generally referred to as wind technology “innovations,” have enabled significant increases in the capacity and electric generation share of wind power in the United States. Achievements of past wind innovations have led to reductions in levelized cost of energy (LCOE) through scaling and controls that enable lower specific power ratings (Wiser et al. 2021; Elia et al. 2020). However, widespread wind energy deployment outside of high-wind-speed geographies has been limited (see Figure ES-1) and has motivation for continued research and development (R&D) investments and exploration of the value proposition of such. To realize the potential capacity of land-based wind energy, continued investment is needed in R&D focused on turbine siting constraints and the spatial implications of ordinances, Federal Aviation Administration height restrictions, and other spatial and technology-scale considerations. Additional innovations are also needed in the areas of turbine scaling, blade segmentation and transportation, advanced manufacturing, the reduction of installation and operations and maintenance (O&M) costs, and plant controls.

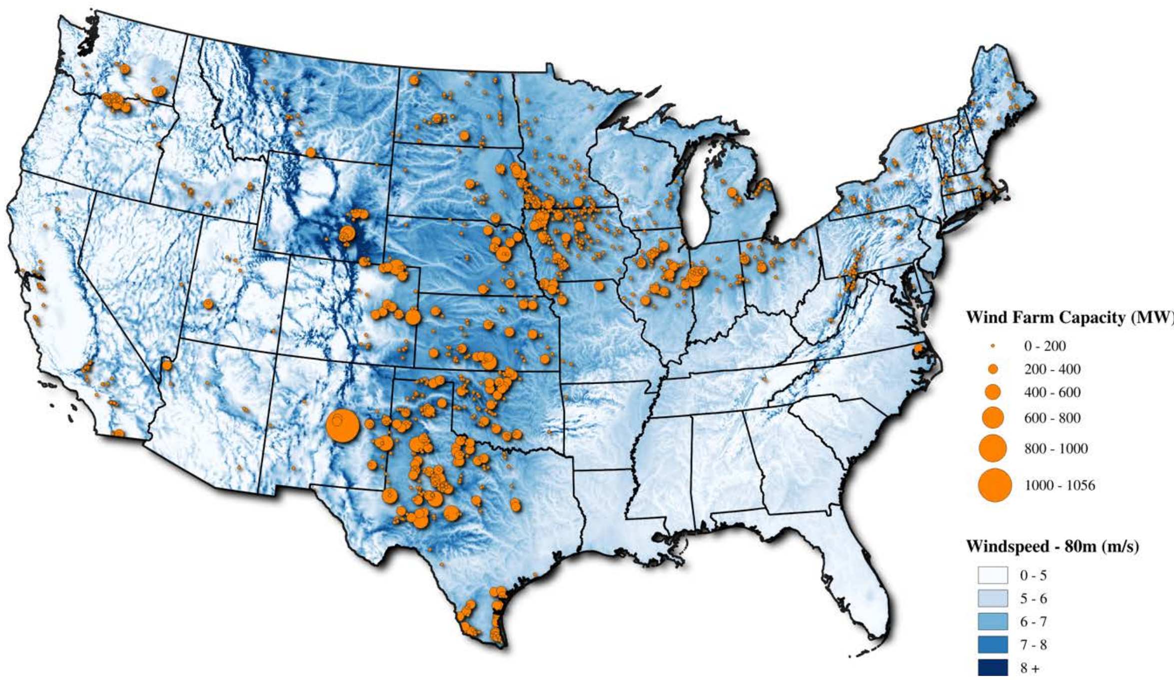

Figure ES-1. Map of installed wind capacity and 2007–2013 average wind speed in the United States in 2021.

Source: U.S. Wind Turbine Database and the WIND Toolkit

This study evaluates the potential of near-term innovations to expand the geographic range of economically viable land-based wind power production in the United States. Many challenges to future deployment of wind power can be associated with increasing concentration in high-wind areas. As more wind power is deployed in these same areas, it is likely that residential and regulatory resistance to further deployment will increase (Lerner 2021; Lopez et al. 2022) and access to transmission may diminish. This analysis aims to emphasize the potential for innovations to enable land-based wind in regions with limited wind deployment to date, especially those with lower quality wind resources.

Methodology Summary

The method used to evaluate this potential expansion combines spatially explicit technical potential modeling with costs and performance parameters associated with a set of technological innovations. These innovations include low-specific-power turbines, advanced towers manufactured on-site, climbing cranes, up-tower operations and maintenance cranes, and wake steering. These technologies are expected to be commercially available in the near future (3 to 5 years). This study does not evaluate the effect of scaling turbine ratings and focuses on a 3-megawatt (MW) machine.

Initial cost and performance estimates were developed in collaboration with industry partners. Land-use restrictions were modeled according to the "Reference Access Scenario" described in Lopez et al. (2021). Balance-of-system capital costs associated with each combination of turbine technologies were generated with the National Renewable Energy Laboratory's (NREL's) Land-Based Balance-of-System Systems Engineering (LandBOSSE) model, wind resource data were pulled from NREL's Wind Integration National Dataset (WIND) Toolkit, and system performance and initial levelized cost estimates were generated using NREL's System Advisor Model (SAM). Across these scenarios we utilize NREL's Renewable Energy Potential model (reV) to coordinate SAM calls across the country, calculate capacity estimates using land-use restriction assumptions, calculate tie-line costs associated with connection to transmission, and refine LCOE estimates. Overall, this modeling pipeline accounts for capital and operating costs, project financing, technological performance, resource availability and variation, land-use restrictions, and access to transmission. A list of limitations of the modeling approach and assumptions is provided in Section 2.2, Key Caveats and Limitations.

Innovations were applied to two different turbines. We assumed a turbine with the characteristics of the 2018 industry average turbine as reported in the *2018 Cost of Wind Energy Review* (Stehly and Beiter 2019) and the low-specific-power 3-MW turbine (see Table ES-1), with the final set of 44 scenarios including each innovation explored in this study. The resulting 44 data sets represent different combinations of innovations and turbine technologies. We then identified which combinations of innovations produce the minimum LCOE at over 57,000 locations in the contiguous United States (CONUS) and built a single "Innovations" data set. To estimate the spatial extent and magnitude of developable capacity for different technology scenarios, we filtered the Innovations data sets to include only sites under an LCOE threshold of 45 dollars per megawatt-hour ($/MWh). While the national average LCOE in 2020 for land-based wind in the United States was $33/MWh according to the *Land-Based Wind Market Report: 2021 Edition* (Wiser et al. 2021), the $45 threshold emphasizes changes in potential in areas with lower wind resource. The filtered Innovations data set is then compared to filtered data sets from both a "Baseline" turbine representing 2018 technology (Table ES-1) and three projected turbines representing 2025 technology. The Baseline turbine configuration was taken from NREL's *2018 Cost of Wind Energy Review* (Stehly and Beiter 2019) while the future turbine configurations were derived from NREL's Annual Technology Baseline (ATB) (NREL 2021). The ATB projects future cost and performance values according to "Conservative," "Moderate," and "Advanced" future technology scenarios, each of which were explored here (see Table ES-2).

Table ES-1. Baseline vs. Innovations Turbine Characteristics

Parameter[a]	Baseline Technology (*2018 Cost of Wind Energy Review*)	Innovations Technology
Turbine Rating (MW)	2.43	3
Hub Height (m)	90	90, 100, 120, 140, 160
Rotor Diameter (m)	116	150
Specific Power (W/m^2)	230	170
Plant Size (MW)	up to 400	up to 400
Fixed Charge Rate (real) (%)	7.2	7.2
Losses (%)	20.8	18.8
Operating Expenditures ($/kW)	44.9	43.47, 43.51, 44.00, 45.07, 45.11
Capital Expenditures ($/kW)	1,185	1,113, 1,160, 1,241, 1,288, 1,359

[a] m = meter; W = watt; kW = kilowatt

Table ES-2. Annual Technology Baseline (ATB) vs. Adjusted Innovations Characteristics

Advancement Scenario	Model	Rating (MW)	Hub Height (m)	Rotor Diameter (m)	FCR[a] (%)	Losses (%)	OpEx[a] ($/kW)	CapEx[a] ($/kW)
Conservative	Innovations	3.0	90	150	4.9	16.7	43.56	1,133
	ATB	4.0	110	150				1,642
Moderate	Innovations	3.0	120	150	4.9	11.8	40.72	1,241
	ATB	5.5	120	175				1,618
Advanced	Innovations	3.0	140	150	4.9	9.4	37.91	1,288
	ATB	7.0	135	200				1,320

[a] FCR = fixed charge rate; OpEx = operational expenditures; CapEx = capital expenditures

Finally, two reference sites were examined in more detail to isolate component-level cost reduction contributions. Eastern Kansas was chosen to represent a high-wind resource site (average 7.69 meters per second [m/s] at 90 m) and central Georgia was chosen to represent a low-wind site (average 5.54 m/s at 90 m). Beginning with the Baseline turbine at each location, innovations were added progressively and LCOE values were recorded until the turbine with all innovations was reached.

Our methods differ from traditional reference site methods (NREL 2021) primarily because we model plant performance, costs, and land use at a much higher spatial resolution (132 square-kilometer [km^2] cells) across larger study areas (i.e., CONUS), and we incorporate the ability to create composite supply curves that allow for site-specific technology selections.

Results Summary

We found that near-term innovations including taller towers and low specific power ratings result in a significant expansion of low-cost wind power across CONUS compared to both the Baseline turbine (Figure ES-2) and the Innovations ATB turbines (Figure ES-3). They have the greatest impact in areas with lower annual average wind speeds, such as the Southeast, Gulf Coast, and East—areas outside of the traditional wind belt with limited existing wind deployment. These results show a larger spatial footprint of low-LCOE wind relative to previous ATB technology and cost assumptions.

Combinations of these innovations result in larger reductions in LCOE at sites with lower wind resource and higher shear, as shown in Figure ES-4. Lower specific power ratings result in larger increases in capacity factor (Figure 8 in the body of the report) while sites with high resource benefit from lower turbine and O&M costs as well as reduced losses due to wake steering and plant controls.

Among the specific technologies explored, those that enable lower specific power ratings and combinations of other innovations such as tall towers and up-tower cranes result in the greatest magnitude of cost reductions and the widest spatial distribution of low-cost land-based wind. Low-specific-power turbines can reduce LCOE significantly at locations with low to moderate wind resource due to higher capacity factors compared to the Baseline technology. Advanced towers reduce LCOE at all locations, and increased hub heights also reduce LCOE at nearly all locations. Innovations such as climbing cranes and up-tower O&M cranes further increase the cost-effectiveness of tall, advanced towers.

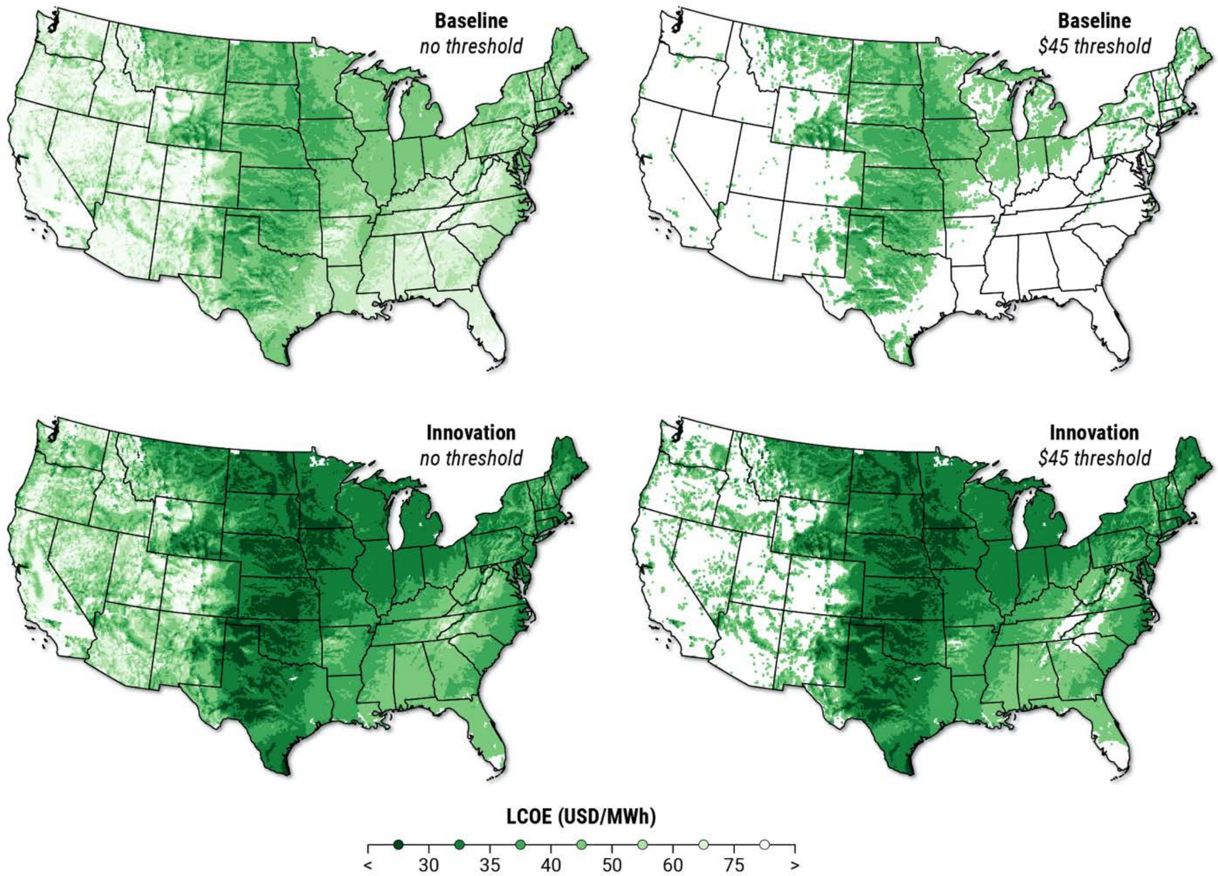

Figure ES-2. National map of LCOE for Baseline and lowest-LCOE Innovations combination with and without a $45/MWh threshold

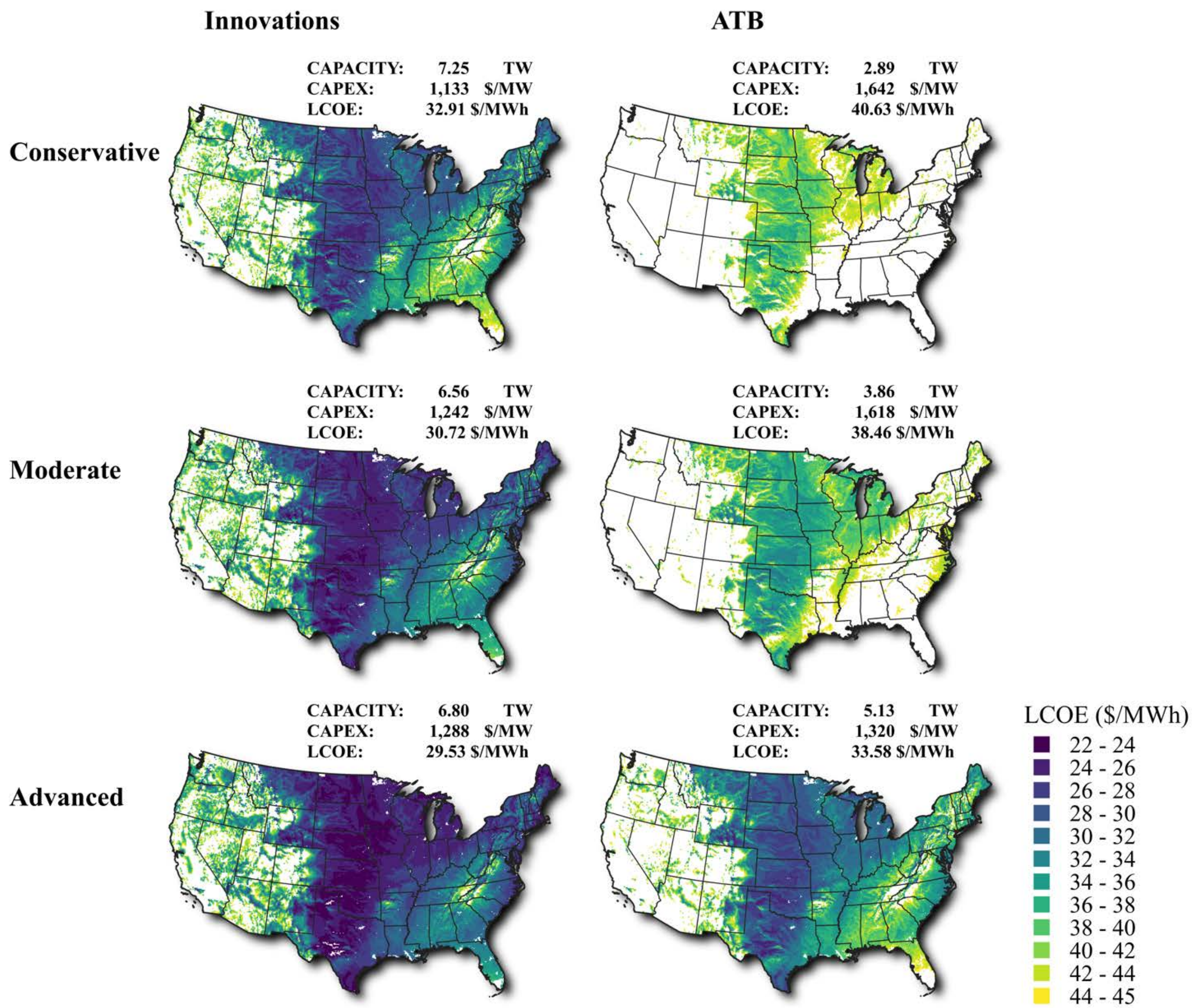

Figure ES-3. LCOE and locations of model wind plants with an LCOE under $45/MWh for the Innovations technology scenarios and the Annual Technology Baseline technology scenarios (2025) after aligning operational expenditures, losses, and fixed charge rate. Total capacity, capital costs, and LCOE associated with each model are displayed above each map.

TW = terawatt

The cost reduction patterns seen at the national scale were reflected in the reference site examination (Figure ES-4). In the high-wind site in Kansas, the largest component reduction resulted from the addition of the low-specific-power turbine (−$15/MWh) while the addition of other components resulted in minimal further reductions. In the low-wind resource site in Georgia, however, the addition of the low-specific-power turbine, taller tower, climbing crane, up-tower O&M crane, and wake steering all contributed significant cost reductions. In this scenario, the cost additions resulting from tower transportation were associated with towers manufactured with spiral welding of a 90-m tower, whereas the cost reductions for the taller 160-m tower were associated with on-site manufacturing technology.

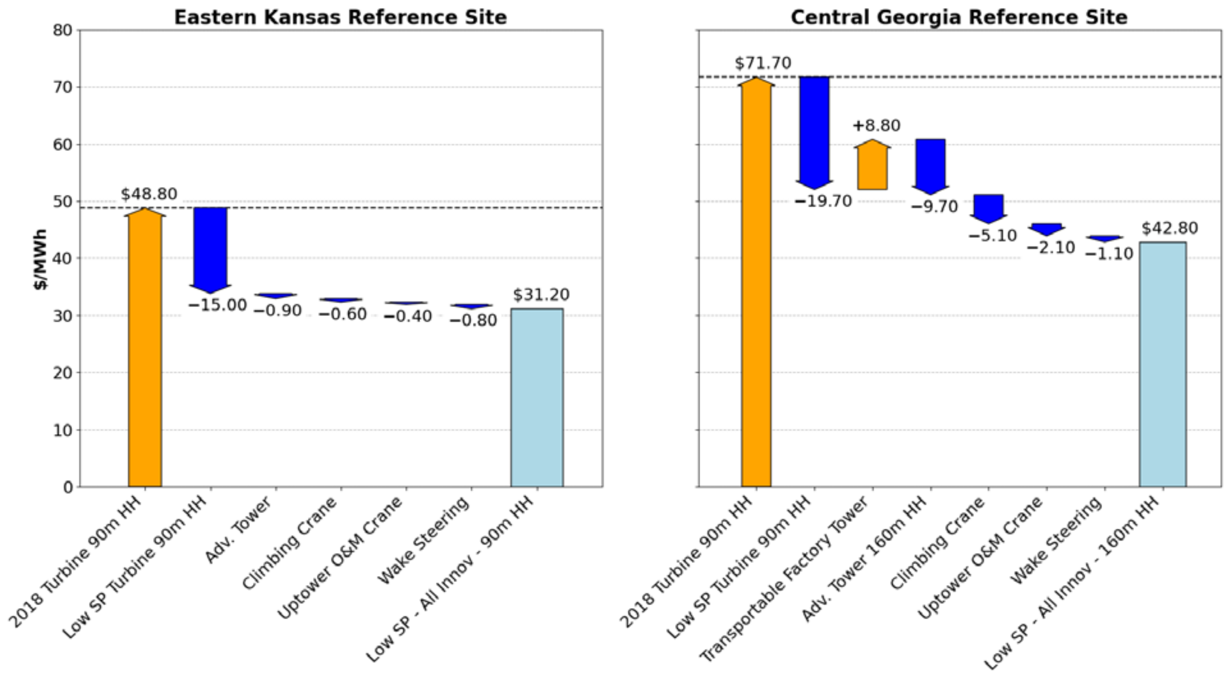

Figure ES-4. Innovations component contribution to LCOE reductions at a high-wind sample site in Kansas and a low-wind sample site in Georgia.

HH = hub height; SP = specific power

Key Takeaways

Of the innovations considered here, low specific power and lower-cost turbine rotor and nacelles result in the largest reductions in LCOE, as illustrated in Figure ES-4. Advanced towers show larger reductions in LCOE as wind resource decreases and shear increases, as shown in Figure ES-4. Recent work by NREL (Bortolotti et al. 2022) on a slightly higher specific power concept but with a higher turbine rating, including a segmented blade, illustrates the potential interest of industry for producing turbines that are similar to our assumed technology. Advanced towers (U.S. Department of Energy [DOE] 2019) also reduce costs for all towers modeled, and on-site manufacturing reduces transportation limits and significantly reduces tower mass and cost as hub height increases relative to conventional transportable towers. Up-tower O&M and climbing cranes also enable LCOE reductions for taller hub heights. Advanced wind farm plant controls and wake steering reduce losses and increase energy capture (Veers et al. 2022).

These results show increased technical and cost potential relative to the ATB technologies, which supports R&D investments in tall towers, on-site manufacturing, advanced plant controls, and blade transportation to enable lower-specific-power turbines. These results also illustrate a significant reduction in LCOE values in low-wind resource areas compared to recent technology (Figure ES-4). The combination of these factors supports industry and utility consideration for wind energy, particularly in low-wind-resource areas. These findings and this approach may also result in differences in capacity expansion model results, especially in high-deployment scenarios (Denholm et al. 2022). The regions observing the greatest impact currently have limited wind deployment, potentially highlighting a need for new approaches to policy, industry, and research strategies that should reflect this new potential; our future work could further elaborate this opportunity.

This suite of innovations also results in earlier cost reduction potential when compared to future cost projections such as the NREL ATB. These methods and tools will be incorporated in future ATB and NREL standard scenarios (Cole et al. 2020) using reV and the Regional Energy Deployment System (ReEDS).

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1 Introduction

Wind energy in the United States has seen rapid growth in the past decade, overtaking hydroelectric power as the largest source of renewable energy in 2019 (U.S. Energy Information Administration [EIA] 2020). However, the geographic footprint of wind deployment to date has been largely concentrated in areas with strong wind resource (Figure 1). According to the 2021 land-based wind market report (Wiser et al. 2021), wind speeds at current wind farms average 7.67 meters per second (m/s) at 80 m above ground level, with most of the installations occurring in the Great Plains. This value is only about 6.26 m/s nationally (Draxl et al. 2015). While wind resource quality and power purchase price are the main drivers for the economic viability of a wind power plant, shadow flicker, noise, local ordinances, transmission and interconnection access, and costs also affect the possibility of deployment. To meet ambitious renewable energy targets and mitigate climate change, the geographic footprint of wind energy in the United States will likely need to expand beyond regions where wind is currently deployed in the United States, as shown in the 2020 standard scenarios results under the low-cost wind scenario (Cole et al. 2020). Such an expansion will require increasing the economic viability of wind energy technology and plants to support deployments.

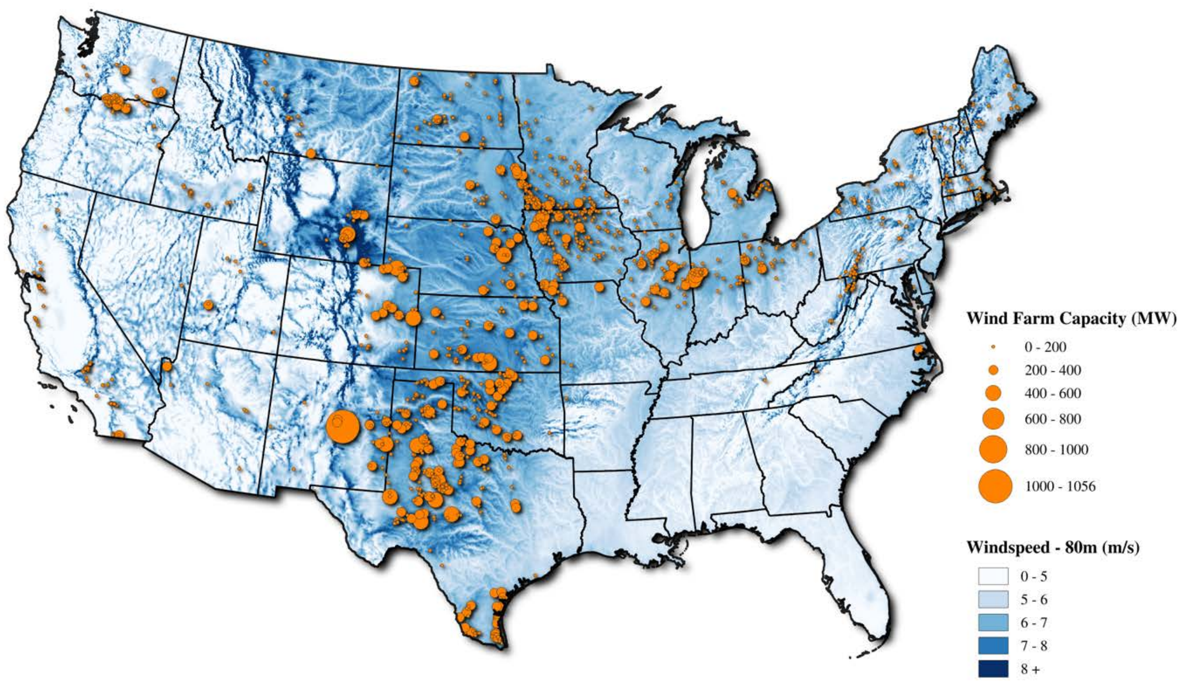

Figure 1. Map of installed wind capacity and 2007–2013 average wind speed in the United States in 2021.

Source: U.S. Wind Turbine Database and the WIND Toolkit

Since 1998, reductions in installed costs, increased capacity factors, advancements in wind turbine controls, reduced financing cost, and reduced operations and maintenance (O&M) costs have reduced the levelized cost of energy (LCOE) of wind by more than 60% (Wiser et al. 2021). Emerging technology innovations could further reduce the cost of wind energy and enable deployment in regions with lower wind resource primarily due to cost reductions and lower specific power ratings (International Panel on Climate Change [IPCC] 2011). Prior research, which has commonly estimated overall cost of energy reductions using expert elicitation and learning curves (Wiser et al. 2021), has revealed significant expected reductions in the cost of energy.

Projections for cost, performance, finance, and O&M costs have been conducted (Mai et al. 2017; Wiser, Bolinger, and Lantz 2019; IPCC 2011; Lamy et al. 2016) as well as research around potential innovation pathways to reduce the cost of wind energy. These efforts include plant-level optimization research (Dykes et al. 2017), national assessments of the value of innovations (Zayas et al. 2015), the enabling of cost reductions through turbine scaling (Bolinger and Wiser 2012; Kooijman 2013; Bolinger et al. 2021; Key, Roberts, and Eberle 2021; Moné et al. 2014), on-site component manufacturing to reduce the logistics cost of transporting large components through efforts such as the U.S. Department of Energy (DOE) Big Adaptive Rotor project (Johnson et al. 2019), tower scaling, and opportunities for controls to enable larger and taller turbines (Dykes et al. 2018). Additional research on turbine cost reductions has shown economies of scale in turbine production and learning by turbine manufacturers with significant cost reduction contributions (Elia et al. 2020).

To quantify the spatial expansion potential of near-term innovations, we compare the final innovations cost potential results to a progression of low-cost but higher-specific-power turbines that align with industry norms. Here, we use the National Renewable Energy Laboratory's (NREL's) Annual Technology Baseline (ATB) turbine assumptions for conservative, moderate, and advanced scenarios for 2025 (NREL 2022). Each of these turbines has a specific power rating of roughly 226 watts per square meter (W/m^2). The 2025 advanced scenario's cost reduction assumptions are more aggressive than even the final innovations run described above. To separate the effect of specific power, we align fixed charge rate (FCR), operational expenditures (OpEx), and generation loss assumptions between the two data sets while holding capital expenditures (CapEx) at their original values for each turbine.

Previous research has examined the potential for technology innovations to increase the deployment opportunity of wind energy in low-resource regions of the United States, specifically focusing on higher hub heights and lower specific power ratings (Bolinger et al. 2021; Lantz et al. 2019). Bolinger et al. (2021) include a calculation of break-even cost for two scenarios of specific power relative to a baseline, which illustrates the differences in distribution of LCOE values by specific power rating. These results are generally consistent with our findings; our methods are similar in approach but with increased spatial representation. Understanding how and where technology innovations might influence the economic viability of wind energy deployment will be essential to develop a cost-effective and timely plan for achieving renewable energy targets and informing where additional barriers might exist.

Here, we aim to illustrate not only the change in cost of energy, technical potential, and spatial footprint of the assumed innovations but also the contribution of components and specific power ratings to changes in the spatial footprint of technical potential. Additional benefits of low-specific-power turbines and wake steering with plant controls include reduced variability of generation and potentially increased market value of energy relative to higher-specific-power turbines (Bolinger et al. 2021), though these factors are not assessed in this study. We explore how the LCOE of wind energy might change across the contiguous United States (CONUS) with five near-term technology innovations: low-specific-power turbines, advanced towers, up-tower O&M, wake steering, and climbing cranes. Our aim is to quantify the cost reductions and changes in performance from these innovations in relative terms while holding other modeling assumptions fixed (e.g., differences between regional energy markets and land costs). This approach enables us to examine the regional cost reductions and explore where and by how much these innovations reduce LCOE. Geographically, this study aims to evaluate the potential for wind energy across CONUS, with a specific focus on areas that have seen low levels of deployment (e.g., parts of the South, Southeast, and Intermountain West). This study finds that near-term innovations in land-based wind technology result in lower LCOE values relative to the baseline technology in nearly every location in CONUS, with larger LCOE reductions in areas with wind resource lower than the current fleetwide average (Wiser et al. 2021). This expansion provides an opportunity for land-based wind to contribute more to the renewable energy deployment and climate mitigation targets of the United States.

2 Methodology

2.1 Overview

Wind potential is often assessed and classified as geographic (resource), technical, and economic potential—each with varying levels of complexity (Lopez et al. 2021). In the literature, varying techniques, assumptions, and thresholds are used to reveal challenges or opportunities. Here, we use technical potential estimates from (Lopez et al. 2021) as a basis for the available land area for wind technology. This provides us with estimated gigawatts (GW) of wind potential while adhering to spatial siting restrictions (legally protected lands, setback requirements, etc.).

We apply economic assumptions associated with innovations and set cost thresholds to quantify and reveal the geographic distribution of wind potential that could see meaningful reductions in LCOE. While we are not proposing a new definition of wind potential, for clarity, we refer to our estimates determined from cost thresholds in this report as *cost potential*. It is important to note that although an expansion in cost potential may be indicative of increased likelihood of wind deployment, there are many site-specific factors that influence the costs to develop, construct, and operate a wind plant. For example, technical potential and capacity expansion modeling of land-based wind power indicate that deployment is sensitive to incentives, turbine siting regulations, changes in turbine scale, social acceptance, and wildlife impacts (Lopez et al. 2021; Mai et al. 2021), as well as transmission access and the likelihood of new transmission construction (Lamy et al. 2016). This study does not examine these additional factors in detail but instead focuses on how wind cost potential might shift due to technology innovations.

To quantify the effects of innovations on future wind production costs and geographic footprints, we employ a technical potential modeling pipeline (Figure 2). We begin by developing a suite of turbine cost and performance configurations for use in a techno-economic generation model. The development of these configurations draws from previous NREL work and industry partners. The configurations contain increasingly innovative combinations of near-future technology parameters, culminating in a configuration of all innovations explored in this paper. We refer to this final configuration as the “Innovations” turbine. Generation and cost estimates across CONUS are developed and passed into a technical potential model that aggregates these values within model wind farm areas. Cost and generation averages are weighted by the amount of available land within each farm after considering likely restrictions on land use. Then, to account for local differences in wind resource, the hub height of the least-cost Innovations turbine is selected at each farm site. A cost threshold over which development is considered unlikely under current market conditions is chosen and used to filter the wind farm data sets. Finally, the filtered data sets are mapped and compared to a current technology “Baseline” case to assess the geographic expansion of cost-competitive farms, national increases in potential capacity, and local differences in LCOE.

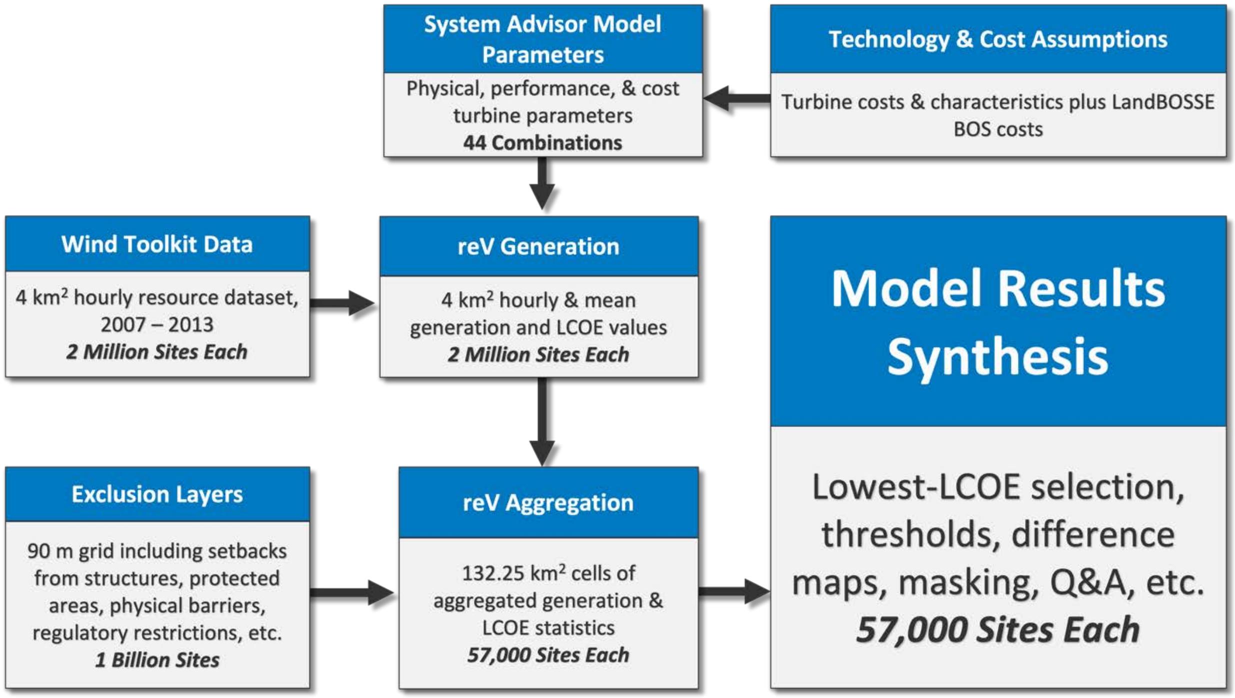

Figure 2. Renewable Energy Potential (reV) modeling pipeline diagram

Additionally, to compare the cost potentials of the Innovations scenario with the well-known ATB, we align operating costs, generation losses, and FCR assumption parameters with the 2030 conservative, moderate, and advanced technology advancement assumptions (NREL 2022) and rerun the model. The geographic expansion of cost potential is then compared to the adjusted Innovations model.

2.2 Key Caveats and Limitations

Several limitations exist in this analysis. The first is assumed land availability. While there is significant uncertainty in the amount of land that will be available for deployment in the future, we use a single land access scenario tailored to match current regulatory barriers and physical constraints on utility-scale wind energy development. Table 1 outlines the land-use constraints used in this analysis and gives a detailed description of each element, which can be found in Lopez et al. (2021).

Table 1. Land Access Exclusions

Siting Exclusion	Description
Setbacks to transmission rights-of-way	Setback of 1.1x wind turbine tip height
Urban areas and airports	Excluded
Radar	4-kilometer [km] buffer around NEXRAD, 9-km buffer around short-range/long-range installations
Documented state and county setback and height ordinances	Excluded
Protected public lands and conservation easements	Excluded
Other federal lands	Excluded
Slope > 25%	Excluded
Mountainous landforms and high elevation (>9,000 feet [ft])	Excluded
Water and wetlands	305-m buffer

The model is also limited in its ability to model transmission costs with high fidelity. Variables such as transmission losses, appropriate routing (avoiding impassable areas), or voltage-dependent costs are currently not implemented. Instead, the model used straight-line distances with standard assumptions for tie-line and connection costs. Competition for transmission capacity is accounted for, though in a rudimentary fashion given the nature of technical potential modeling. In cases where plants are unable to connect to any feature because of capacity limits, they are routed to the nearest population center, which absorbs generation at significantly higher costs due to the increased distance.

We assume a turbine with a 3-megawatt (MW) rating and 150-m rotor diameter based on input from dialogue with industry-leading original equipment manufacturers as the Innovation turbine technology. This results in a specific power rating, defined as the rated electrical output of the generator divided by the swept area of the rotor, of 170 W/m^2, which is lower than all commercially available turbines in the United States. Notably, General Electric (GE) has continued to explore the feasibility of low-specific-power turbines for higher ratings based on the Sierra platform using segmented blades (Bortolotti et al. 2022). This turbine configuration and associated costs are most appropriate for an International Electrotechnical Commission (IEC) Class 3 site suitability. Typically, as wind resource decreases, specific power ratings resulting in the minimum LCOE decrease. We assume this turbine is suitable at all locations, which will result in higher capacity factors than may be expected at sites with a stronger wind resource.

Our assumptions for turbine and tower technologies are based on input from industry partners, but some uncertainty exists in the specific technologies, configurations, and costs assumed in this analysis. All these technologies are in development and are either in the demonstration or early commercialization phases and are not guaranteed to be offered commercially in the assumed timeframe.

We assume towers and tower costs from Keystone Tower Systems that will be manufactured on-site at each potential wind farm location as the tower technology for the Innovations technology. Due to mobilization costs for the manufacturing equipment for the advanced tower, we underestimate the cost of towers for hub heights greater than 110 m for projects less than 200 MW. We assume a single rotor and nacelle configuration with a single specific power rating that is significantly lower than the current industry average. We also assume this low specific power rating for all sites, regardless of the strength of the wind resource. It is unlikely that a single specific power would be optimal or suitable across a wide range of wind resource strengths and unlikely that a single rotor nacelle configuration would be suitable across a wide range of wind resource strengths. Given this, it is possible that the assumed configuration will produce relatively higher LCOE values at higher wind resource sites, as compared to a turbine tailored specifically to higher wind speed sites.

2.3 Baseline Scenario

The *2018 Cost of Wind Energy Review* (shortened to COWER for ease of reference) technology assumptions were used for our Baseline scenario (Stehly and Beiter 2019). The COWER annual report estimates component-level performance, costs, and LCOE for a representative plant and turbine in the United States. We did not use the capital costs from the original assessment; instead, the physical components were used while the costs were updated to reflect costs based on industry input. The 2018 COWER turbine configuration costs were estimated with industry partners supplying nacelle, rotor, and tower costs and the NREL Cost and Scaling Model, (Fingersh, Hand, and Laxon 2006) which uses component-level scaling relationships to estimate turbine component costs. We used NREL's Land-Based Balance-of-System Systems Engineering (LandBOSSE) cost model as well as estimated turbine transport costs. This resulted in a more direct comparison of the impacts of specific power and innovations relative to the 2018 COWER turbine configuration. The COWER turbine assumptions are summarized in Table 2 and the power curves for the COWER turbine and low-specific-power turbines are shown in Figure 3.

Table 2. Baseline vs. Innovations Turbine Characteristics

Parameter	Baseline Technology (NREL 2018 COWER)	Innovations Technology
Turbine Rating (MW)	2.43	3
Hub Height (m)	90	90, 100, 120, 140, 160
Rotor Diameter (m)	116	150
Specific Power (W/m^2)	230	170
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Losses (%)	20.8	18.8
Operating Expenditures ($/kW)[a]	44.9	43.47, 43.51, 44.00, 45.07, 45.11
Capital Expenditures ($/kW)	1,185	1,113, 1,160, 1,241, 1,288, 1,359

[a] kW = kilowatt

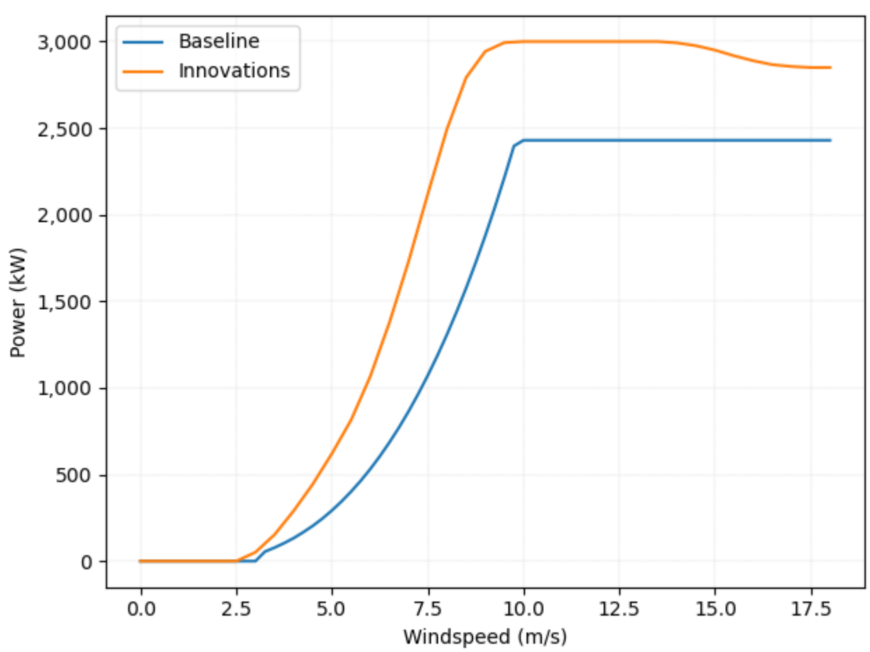

Figure 3. Power curves for the Baseline and Innovations turbines

2.4 Innovations

We define the innovations technology scenario, referred to as "Innovations" in this report, to represent technologies that will be commercially available by 2025. The costs and performance assumptions used for this scenario are based on input from industry partners and are subject to market forces, macroeconomic factors, and other factors. Using our modeling pipeline, we analyzed five sets of innovations: low-specific-power turbines, advanced towers, up-tower O&M, wake steering, and climbing cranes. Each set of innovations technologies are also modeled at multiple hub heights: 90, 100, 120, 140, and 160 m.

2.4.1 Low-Specific-Power Turbines

Specific power refers to a ratio between the turbine capacity and its rotor-swept area. Lower specific power generally results in higher capacity factors for a given turbine and resource (Wiser et al. 2021). However, optimal specific power rating is a function of wind resource strength, turbulence intensity, design life, turbine rating, turbine component cost and scaling relationships, mechanical loads and controls, transportation costs, and balance-of-system (BOS) cost and scaling.

Since 1998, specific power ratings for the U.S. turbine fleet have decreased (Wiser et al. 2021). In addition to new turbines lowering specific power, existing turbines can be partially repowered or retrofitted with new rotors and generators to have lower specific power ratings. Since 2015, more than 9,200 MW of capacity have seen reductions in specific power, with 3,087 MW in 2020 alone. This has resulted in an average specific power of 251 W/m^2 for the 9,200-MW repowered fleet after retrofit compared to an average specific power of 334 W/m^2 prior to retrofit (Wiser et al. 2021).

Building on this historical trend, one of the innovations that we consider is lower-specific-power turbines. Because specific power is also a product of innovations in controls, materials, design standards, blade design, and system optimization (Liew et al. 2020; Johnson et al. 2019), we consider these broader system-level optimizations enabled by advanced controls to also be included in our low-specific-power turbines category of innovations (Bolinger et al. 2021).

For this study, industry partners provided cost and performance estimates for a 3-MW, 150-m-rotor-diameter turbine with a specific power rating of 170 W/m^2 and an estimated commercial offering in 2024–2025. The turbine assumed in this study has a lower specific power rating than the U.S. industry average for IEC Class 3 site conditions (Wiser et al. 2021) and also utilizes a low-wind-speed cutout approach to minimize loads and enable longer blades (Swisher et al. 2021). To account for the difference in cost associated with the 2.4-MW Baseline turbine and the 3-MW Innovations turbine, we combined the turbine and tower costs for each turbine (also provided by industry partners) with estimated BOS costs (computed using the NREL LandBOSSE model).

2.4.2 Advanced Towers

As turbine hub heights and ratings increase, the cost of the turbine tower increases due to more components combined with geometric and axle load constraints for transportation. Tower base diameters are typically constrained to between 4.3 and 4.6 m depending on transport route in the United States (Mooney and Maclaurin 2016). Advanced tower designs have the potential to mitigate these increases in cost through novel manufacturing techniques that eliminate transportation constraints (e.g., on-site manufacturing). There are a variety of advanced tower designs that are under development, including spiral welding technology (Keystone Tower Systems Undated) and 3D-printed concrete tower bases (Kruger 2020). In this study, we model spiral welding technology, and industry partners provided cost and mass estimates for their spiral welded towers. In our analysis, we assume that all conventional towers at all hub heights (90–

160 m) and all towers in the range of 90–120 m are highway-transportable, whereas the 140-m and 160-m towers are manufactured on-site with a mobile factory.

2.4.3 Up-Tower O&M

As hub heights increase, O&M costs may increase due to larger and taller cranes required for major component replacements (e.g., gearbox, generator, main bearing, blade, and other component replacement) (Poore and Walford 2008). Wood Mackenzie estimates a 40% cost savings from up-tower cranes vs. mobile cranes for single mobilization (Liu 2020) and cites crane availability and demand as a key cost driver to U.S. O&M through 2030 (Liu 2021). Self-hoisting cranes such as the Liftra LT1200[1] may reduce the mobilization cost relative to a conventional crawler crane for major component replacements and service such as gearbox, generator, and main bearing replacements as well as enable removal and installation of the rotor for blade, hub, and pitch system repairs on the ground.

As hub height increases, the potential cost savings for performing major component replacements using up-tower cranes increase relative to conventional cranes. We collaborated with industry partners to develop cost and labor estimates for up-tower cranes, and we worked with current industry turbine maintenance service providers to estimate these values for conventional cranes.

2.4.4 Climbing Cranes

Conventional cranes such as crawler or mobile cranes are typically used to install the turbine tower, nacelle, and rotor. As component mass and hub height increase, the size and cost of conventional cranes increase for two reasons: (1) the rental rate and mobilization cost for the equipment increases and (2) the cost of disassembly and reassembly, or breakdown, of the crane during movement between turbine sites increases (there is higher likelihood of a required breakdown as crane size increases). Climbing cranes reduce the costs associated with turbine erection because they can operate with a lower mobilization cost, and they require fewer breakdowns than conventional crawler cranes. For this study, we assume a climbing crane similar to the Liftra LT1500 concept,[2] which enables installation of turbines up to hub heights of 250 m. Cost estimates were developed in coordination with Liftra for the equipment mobilization and rental cost, labor hours and rates, wind delay thresholds, and cycle times for component installation and breakdown between wind turbines. These assumptions were used in the NREL LandBOSSE model (Eberle et al. 2019) to estimate turbine installation costs.

2.4.5 Wake Steering

Wakes produced from turbines within a wind power plant can reduce plant-level energy production. To mitigate the loss of power production, developers are starting to implement advanced controls on turbines, which minimize the wake effects typically by yawing the turbines to redirect, or steer, wakes to avoid downwind turbines (Doubrawa and Moriarty 2021). This practice is generally referred to as wake steering. Wind resource, turbulence intensity, turbine specific power, wind speed frequency and direction distributions, and especially turbine spacing drive the potential for wake steering to increase annual energy production (AEP) (Bensason et al. 2021). Key benefits of wake steering may be siting flexibility and increased plant capacity

[1] https://liftra.com/product/lt1200-liftra-self-hoisting-crane/
[2] https://liftra.com/product/lt1500-liftra-installation-crane/

density for an equivalent cost of energy (Bensason et al. 2021). For this study, we assume wake steering contributes a constant 2% reduction in losses based on results from Bensason et al. (2021) showing higher AEP gains from wake steering as annual average wind speed decreases and based on holding the assumed capacity density constant at 3 MW/km^2. Specific results from Bensason et al. (2021) of a 150-W/m^2 turbine in a farm of 49 turbines at a square 6-rotor-diameter (D) relative rotor spacing, or ~3.2-MW/km^2 capacity density and 6-m/s annual average wind speed, show a wake loss reduction opportunity by employing wake steering of 2.5%. This value decreases as annual average wind speed increases and decreases as relative rotor spacing increases. We assume a 2% reduction in losses because of wake steering as annual average hub-height wind speeds for LCOE values less than 45 dollars per megawatt-hour ($/MWh) are greater than 6 m/s. This is an approximation, as we were unable to model site-specific plant layouts and wake losses. At the time of this analysis there were no available wake models capable of capturing the potential difference of employing wake steering at the spatial resolution of our model.

2.5 Modeling Pipeline

We leveraged and expanded four NREL models and tools to develop our modeling pipeline: LandBOSSE, the System Advisor Model (SAM), the Wind Integration National Dataset (WIND) Toolkit, and the Renewable Energy Potential (reV) model (Figure 2). To estimate how BOS costs might change as wind plants and turbines increase in size, we utilize the LandBOSSE model, which relies on process-based and empirical modeling to estimate BOS capital costs incurred during construction of a land-based wind plant.

The WIND Toolkit (Draxl et al. 2015) is used as the resource input. The WIND Toolkit is a spatio-temporal wind resource data set built using the National Center for Atmospheric Research's Weather Research and Forecasting model. It stores wind speed, wind direction, air pressure, temperature, relative humidity, and turbulence variables at multiple altitudes to provide appropriate resource data for a range of turbine heights. It provides 7 years (2007–2013) of hourly data points on a 2-km grid and is used as an input to SAM (Blair et al. 2018).

SAM is a techno-economic energy production model used to develop time series of generation estimates and an average LCOE value for a given time series from a resource data set. To compute LCOE, SAM uses the following equation:

$$LCOE = \frac{1000 \times (CapEx \times FCR) + OpEx}{AEP_{net}}$$

where *LCOE* is the levelized cost of energy ($/MWh), *FCR* is the fixed charge rate (%), *CapEx* is capital expenditures ($/kW), AEP_{net} is net annual energy production (MWh), and *OpEx* is annual operational expenditure ($/kW) (Stehly and Beiter 2019). CapEx includes the total installed cost of the project, including costs for turbine, tower, and transport, and BOS costs including construction of roads, foundations, collection system, substation, turbine installation, etc. FCR represents the amount of annual revenue required to pay the carrying charge (NREL 2021). We assume a 7.5% FCR (real) value for this analysis as reported in the NREL *2018 Cost of Wind Energy Review* (Stehly and Beiter 2019). OpEx includes costs to operate and maintain the wind plant, including major component replacement, minor corrective maintenance, balance of plant, property tax, insurance, asset management, and other costs. The 2018 report (Stehly and

Beiter 2019) cites Wiser, Bolinger, and Lantz (2019) as the source of the assumed operations and maintenance costs. AEP_{net} is calculated using SAM and the WIND Toolkit for each turbine, assuming their turbine power curve. AEP_{net} includes wake, availability, electrical, and blade soiling losses.

The reV model is used to model technical and cost potential across landscapes (Maclaurin et al. 2019). It is split into two submodules: reV-Generation, which coordinates SAM to run technologies at every available resource point, and reV-Aggregation, which aggregates the 4-km^2 generation time series and LCOE values into 132.25-km^2 areas that represent individual wind farms. It also uses a 90-m grid of land-use restrictions to exclude areas where wind development is not likely to occur (e.g., infrastructure, protected land, water bodies, setbacks). We use two land exclusion data sets: one that considers setbacks for a reference 90-m turbine, and another that considers setbacks for a taller, future turbine set at 135 m. In this study, due to computational constraints, the reference setback layer is used for the turbines with 90-m and 100-m hub heights, and the future setback layer is used for the turbines with 120-, 140-, and 160-m hub heights. A detailed description of the reference land-use layer can be found in Stehly and Beiter (2019), and a detailed description of the future land-use layer can be found in Lopez et al. (2021). Aggregated farm capacity is calculated by multiplying the available area after exclusions with a constant capacity density of 3 MW/km^2 (Lopez et al., 2021). When calculating the aggregated mean LCOE and capacity factor values, each 4-km^2 value is weighted by the number of unexcluded 90-m cells within, such that

$$LCOE_{farm} = \frac{\sum_{i=1}^{n}(LCOE_i \times ncells_i)}{\sum_{i=1}^{n}(ncells_i)}$$

where $LCOE_{farm}$ is the weighted LCOE value of the aggregated model farm, $LCOE$ is the original unweighted LCOE value, and $ncells$ is the number of unexcluded 90-m grid cells in the model farm area.

Our goal is to examine the relative differences in remaining capacity between the Baseline and Innovations cases after applying an LCOE threshold. It should be noted, though, that overall capacity estimates for the Innovations turbines will be significantly lower than for the Baseline turbine because taller machines require larger infrastructure and building setbacks. Empirically, larger machines would also decrease capacity density, assuming a constant relative rotor diameter spacing; however, we are using a constant capacity density assumption in these model runs.

Thus, for our typical comparative cases where the Innovations turbines have a significantly higher tip height than the Baseline case, the capacity estimated by cell and nationally is likely significantly *lower than is empirically likely* as tip heights and tip height differences between turbines increase (Stanley et al. 2021). We acknowledge this discrepancy; however, we expect that other factors such as the price of power, installed costs, and site optimization of turbine placement may be larger factors in the overall error in cost potential.

2.6 Output Synthesis

The outputs from reV-Aggregation are synthesized to account for appropriate local turbine height selections, apply cost potential thresholds, build LCOE difference maps, and build masked layers that quantify the amount of additional capacity from the Baseline case to the Innovation cases.

To select locally appropriate turbines, we choose the hub height associated with the lowest LCOE at each wind farm within any one technology group. All values associated with that hub height (LCOE, capacity, capacity factor, etc.) are assigned to that site. For example, the near-future case with all innovations included are modeled nationally at hub heights of 90, 100, 120, 140, and 160 m, and the turbine selection process results in a single data set with the hub heights shown in Figure 4. We do not apply this process to the Baseline case because the 90-m-hub-height turbine represents the industry average for current installations in the United States.

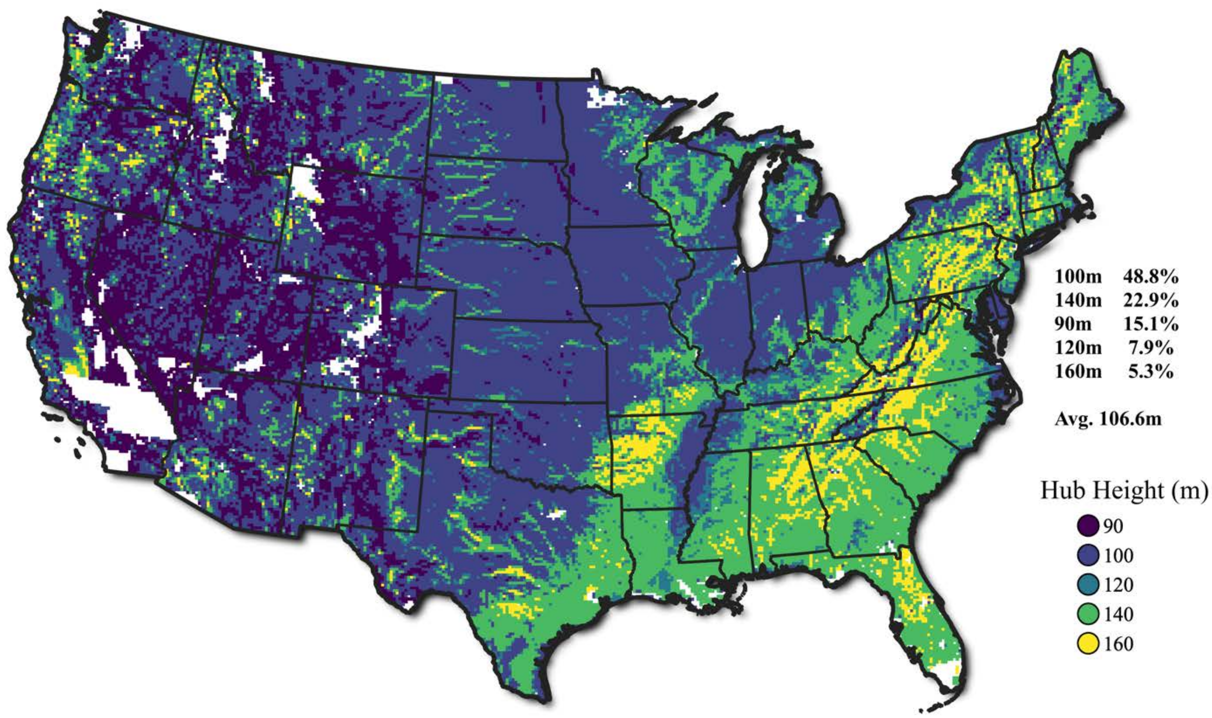

Figure 4. Hub heights included after the least-cost turbine selection process is applied to the Innovations case

To estimate the spatial extent and magnitude of developable capacity for different technology scenarios, we filter the least-cost data sets to include only sites under an LCOE threshold of $45/MWh. The national average LCOE value in 2020 for land-based wind in the United States was $33/MWh, according to the 2021 wind market report (Wiser et al. 2021). We assume a $45/MWh LCOE threshold for this analysis, which is significantly higher than the national LCOE average in 2020 but emphasizes the change in cost potential of innovations in areas with lower wind resource. Since many of the challenges to future deployment of land-based wind energy include social and environmental factors as well as access to transmission, this analysis aims to emphasize the potential for innovations to enable land-based wind in locations with lower resource and better access to transmission. Separately, to quantify the magnitude of changes in LCOE, we build percent difference maps between the Baseline case and each Innovation case.

To illustrate the importance of individual innovation components, we extract LCOE values of increasingly innovative technology scenarios at representative sites in the Southeast and in the Great Plains and compare each to the Baseline case. At both sites, we cumulatively add innovation technologies to the Baseline 90-m turbine, calculate LCOE, and report incremental reductions in percentage terms.

To compare the effect these innovations might have on national deployment potential to common assumptions of technological and cost advancements, we also perform a comparison with model results using the ATB 2030 advancement scenarios. To do so, we retrieved the reV model outputs from Lopez et al. (2021), which used the ATB's 2030 conservative, moderate, and advancement cost scenarios, and reran the Innovations turbines using the same annual operating costs, FCR, and generation loss assumptions. Capital costs for the Innovations turbines were not aligned. We then apply the same LCOE threshold to each of these runs and map the resulting cost potential. Because the turbines with the least-cost hub heights are not available for the ATB outputs, we match each with the individual Innovations hub heights as closely as possible. The system configuration parameters for this comparison are outlined in Table 3.

Table 3. Annual Technology Baseline vs. Adjusted Innovations Characteristics

Advancement Scenario	Model	Rating (MW)	Hub Height (m)	Rotor Diameter (m)	FCR (%)	Losses (%)	OpEx ($/kW)	CapEx ($/kW)
Conservative	Innovations	3.0	90	150	4.9	16.7	43.56	1,133
	ATB	4.0	110	150				1,642
Moderate	Innovations	3.0	120	150	4.9	11.8	40.72	1,241
	ATB	5.5	120	175				1,618
Advanced	Innovations	3.0	140	150	4.9	9.4	37.91	1,288
	ATB	7.0	135	200				1,320

3 Results

We executed our modeling pipeline for our 2018 Baseline plant with no innovations and the Innovations plant configurations with our five technology innovations. Though our results show relative changes in the cost potential of land-based wind energy, they are not intended to identify specific locations where wind deployment is most feasible. These results do not indicate the viability of a specific location to produce competitive energy prices, as local market prices and other factors vary by location. For the purposes of this study, we chose to filter our results using an LCOE threshold of $45/MWh and to present absolute and relative LCOE and capacity results for two primary scenarios: 2018 Baseline plant (fixed 90-m hub height) with no innovations and an Innovations plant with the combination of hub heights and innovations resulting in the lowest LCOE value by cell. We chose the $45/MWh LCOE threshold, as it aligns with DOE Wind Energy Technologies Office Government Performance and Results Act LCOE trajectory for 2020–2021 (Stehly, Beiter, and Duffy 2020). Our LCOE threshold is used for illustrative purposes to visualize and quantify differences in cost potential between Innovations and the Baseline technology. Alternate assumptions (e.g., capital costs, operating costs, losses, and finance rates) and LCOE thresholds could result in significantly different results for Innovations and the Baseline technology. However, these results are intended to show the relative difference between the Baseline technology and Innovations to illustrate significant changes in the magnitude and spatial distribution of $45/MWh potential of land-based wind energy.

3.1 Change in Cost Potential

Figure 5 shows where an LCOE of less than $45/MWh for land-based wind may be realized under two scenarios: 2018 Baseline plant (fixed 90-m hub height) with no innovations and the Innovations plant with the lowest LCOE hub height by cell. These results indicate that innovations may represent increased opportunity for deployment of land-based wind energy in CONUS, specifically in regions with less wind deployment currently. See Appendix A for details on sites that result in lower LCOE for the Baseline technology.

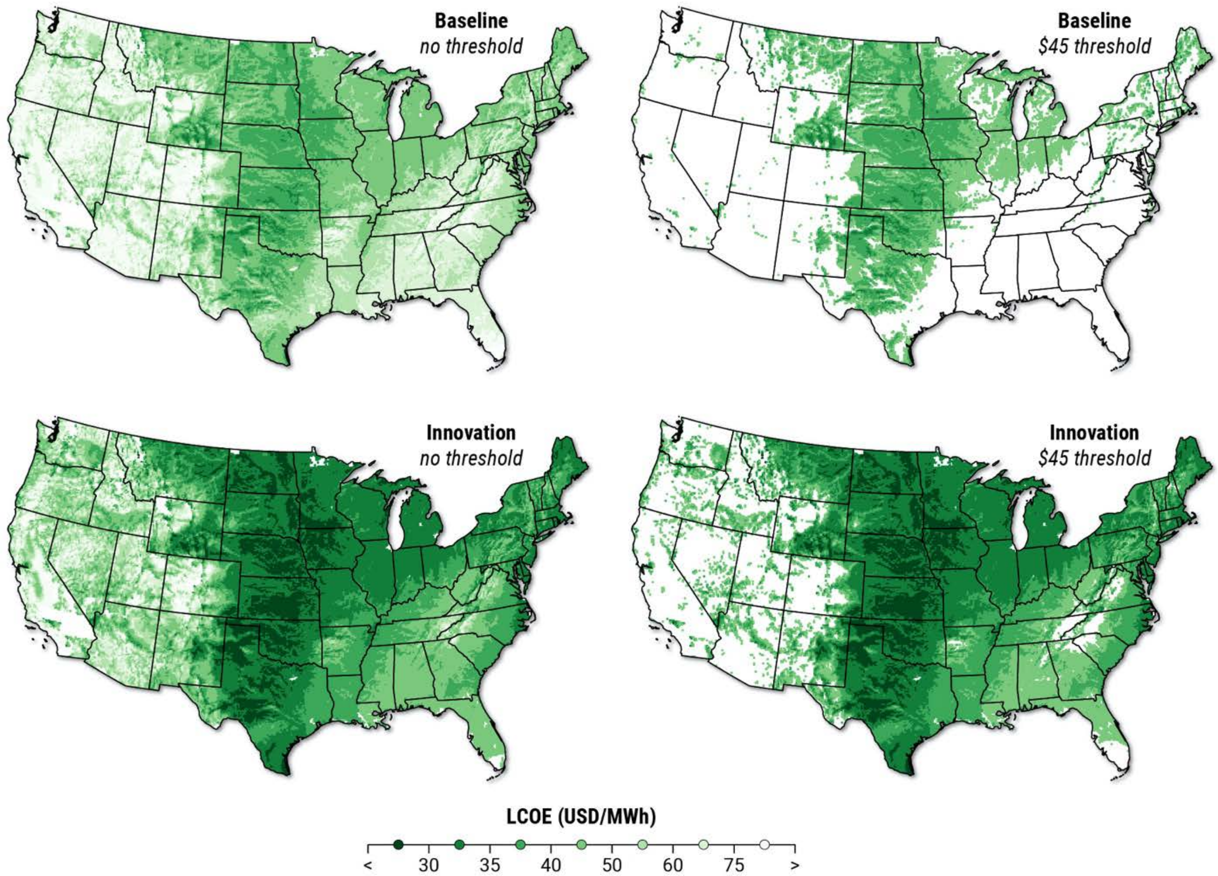

Figure 5. National map of LCOE for Baseline and lowest LCOE Innovations combination with and without a $45/MWh threshold

3.2 New Cost Potential and Change in LCOE

Figure 6 shows areas where Innovations produce LCOE values below $45/MWh and excludes areas where Baseline technology produces LCOE values below $45/MWh. The intent of this map is to show additional areas of sub-$45/MWh wind energy achieved by Innovations over the Baseline; these are areas of "new" cost potential that can be realized through technology innovations. Darker coloring in the figure indicates areas where Innovations present greater opportunities for cost reductions (e.g., a larger reduction in LCOE relative to the Baseline case). Our results show that near-term innovations increase national cost potential for wind energy by 2.84 terawatts (TW) (or 83%) relative to the Baseline technology under an LCOE less than $45/MWh. Areas with limited or no cost potential for low-cost wind in the 2018 Baseline scenario (e.g., the Southeast, Northeast, and Gulf Coast regions of the United States) show large amounts of cost potential in the Innovations scenario, with an increase of 1.23 TW of cost potential.

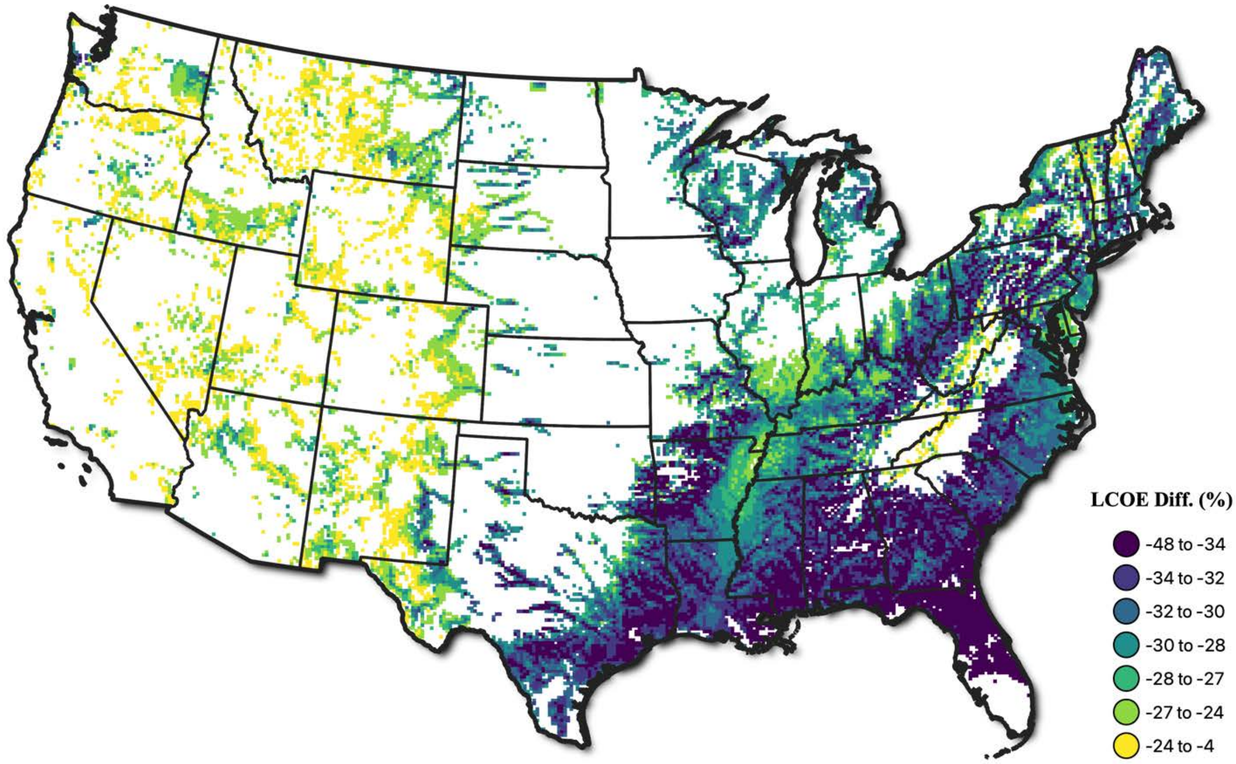

Figure 6. National map of areas where Innovations LCOE < $45/MWh, excluding areas where 2018 LCOE < $45/MWh. This represents areas of new cost potential due to the innovation technologies explored in this paper.

These results show that near-term technology innovations result in lower LCOE values in almost all locations across CONUS and thus increase flexibility for wind energy siting in the United States. These results also illustrate the potential for innovations to present larger reductions in LCOE in areas of moderate to low wind resource and high shear, such as the Southeast, primarily due to the lower specific power rating and the cost of the assumed turbine configuration for near-term innovations. For example, while the average reduction in LCOE for areas shown in Figure 6 is 25%, large areas in the Southeast, Northeast, and Gulf Coast regions have LCOE reductions greater than 30%.

The new cost potential of 1.23 TW in these regions is 43.3% of the national cost potential increase from the modeled innovations. These regions currently have little wind deployment, and with the large increase in cost potential from innovations, they may represent a large amount of cost-effective wind potential and deployment.

3.2.1 Transmission Cost and Utilization

Near-term innovations result in a wider spatial footprint and may result in significantly different spatial and temporal deployment of wind power in capacity expansion modeling scenarios. This is likely due to the relationship of differences in turbine specific power and spatial and altitudinal differences in wind resource. Much of the additional potential from the innovations occur in regions where current wind deployment is limited. This difference in spatial and temporal potential may reduce necessary new transmission infrastructure (Cole et al. 2019) if wind is cost-effective in these regions. These innovations may represent increased opportunity to deploy wind sooner due to current transmission availability in areas rich in wind potential such as the interior of the United States. However, potential barriers to deployment in these new regions include developer, utility, and social lack of experience and increased risk to develop a new market for wind energy. Significant future work by DOE, the wind industry, policymakers, environmental groups, the Federal Aviation Administration, and the U.S. Department of Defense, as well as additional social engagement is likely needed to increase deployment in these regions with limited existing wind deployment (NREL Undated).

Figure 7 shows the difference in the levelized cost of transmission (LCOT) between the 2018 industry average turbine with no innovations and the minimum LCOE solution for all innovations. The difference in LCOT values are below the national average in the Southeast, and the difference in LCOT between the two cases is largest in the Southeast. Larger differences in LCOT values specifically in the Southeast are the result of higher capacity factors due to lower specific power and higher hub heights and lower total plant costs for the Innovations turbines. This further supports the potential for wind energy deployment in the Southeast.

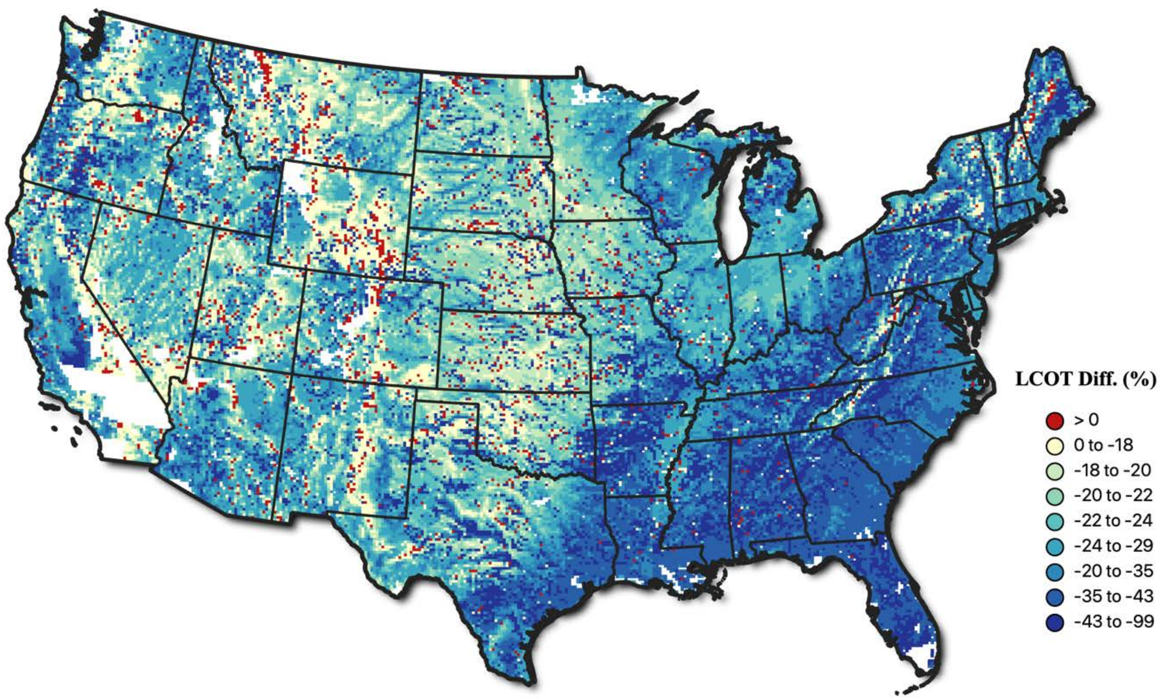

Figure 7. National difference of LCOT of lowest LCOE Innovations case vs. LCOT of 2018 industry average turbine

3.3 Component Contributions to LCOE Reductions

To understand the contribution of each innovation to a change in LCOE at a specific site, we calculated the contribution of individual innovations for two representative sites: eastern Kansas and central Georgia. Table 4 shows the turbine and resource characteristics at each reference site used in the component-level innovation value comparison. Figure 8 shows waterfall charts of the

LCOE components at each site. For each site, the Baseline technology at a 90-m hub height is assumed to be the starting point (left side of the waterfall chart) and is compared to the combination of innovations resulting in the lowest LCOE for hub heights 90 to 160 m (reductions or increases in LCOE due to individual innovations are successively added from left to right). We find that total LCOE reductions due from the near-term scenario relative to the 2018 Baseline scenario are 36.1% and 40.3% at the Kansas and Georgia sites, respectively.

Table 4. Component Contribution Reference Site Conditions

Parameter	Kansas Reference Site	Georgia Reference Site
Annual Average Wind Speed at 90 m (m/s)	7.69	5.54
Power Law Shear Exponent	0.2	0.28
Hub Height Modeled (m)	90	160
Hub Height Annual Average Wind Speed (m/s)	7.69	6.51

The innovation that contributes the most to LCOE reduction at both sites is the low-specific-power turbine. This innovation decreases LCOE by 15% and 19% at the Kansas and Georgia sites, respectively. These reductions in LCOE are due to increased energy production and lower cost of the low-specific-power turbine combined with the increase in turbine rating.

For the central Georgia site, the lowest LCOE for all innovations considered occurs at a 160-m hub height. The third column from the left in Figure 8 shows the increase in LCOE that results from an increase in hub height from 90 to 160 m. However, the higher hub height allows for additional LCOE reductions to be realized through increased energy production at low resource and high shear when combined with lower specific power ratings, reduced costs to increase hub height due to the advanced on-site manufactured towers, climbing cranes, and up-tower O&M cranes.

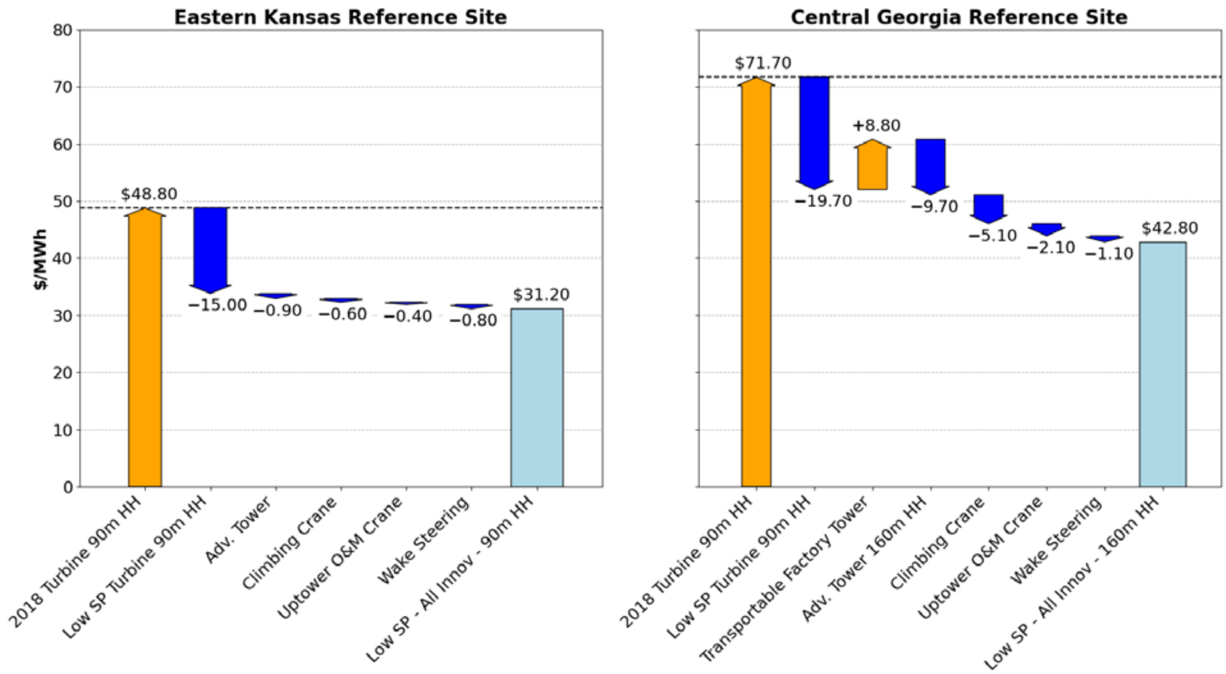

Figure 8. Innovations component contribution to LCOE reductions at a high-wind sample site in Kansas and a low-wind sample site in Georgia

For the Kansas site, the hub height resulting in the lowest LCOE for any combination of innovations is a 90-m hub height due to the strong wind resource and low increase in energy production of the Innovations turbine relative to the increased cost of tower, installation, and O&M. Other innovations such as climbing cranes and up-tower O&M cranes increase their cost-effectiveness as hub height increases due to lower cost scaling than conventional cranes.

Of the innovations considered, the low-specific-power, 150-m-rotor-diameter, 3.0-MW rotor nacelle assembly and associated cost results in the majority of the LCOE reduction relative to the Baseline technology and cost.

4 Discussion

Our results show there is significant potential for wind power at sites with moderate to lower wind speeds due to innovations. Of the innovations considered, the majority of LCOE reduction is due to increased energy capture and higher capacity factors than the baseline technology, each with their respective cost reductions. Physical turbine scaling, advances in controls resulting in load reductions and component mass reductions, materials, manufacturing efficiencies, lower labor rates, and other factors have led to significant cost reductions over the past 20 years of wind technology (IPCC 2011). These cost reductions have been accompanied by reductions in specific power ratings, which, when combined with the features described above, have reduced LCOE significantly (Wiser et al. 2021). Notwithstanding changes in the broader macroeconomic conditions, our research demonstrates that near-term innovations could continue this downward trajectory to a point where low-cost wind energy is widespread across the contiguous United States.

Innovations increase the spatial footprint of wind energy in the United States at a given LCOE threshold relative to the baseline assumptions. Innovations result in lower LCOE values in almost all locations and thus increase the number and diversity of locations for wind energy siting in the United States. Of note, these increases are particularly large in areas with lower annual average wind speeds where wind development is minimal or nonexistent. This is primarily due to the Innovations turbine low specific power rating and corresponding cost resulting in higher capacity factors for a given wind resource with similar CapEx values to the Baseline technology. Figure 9 shows the national relative difference between the 90-m Innovations turbine capacity factor and the Baseline technology turbine capacity factor, nationally. The scatter plot shows the same data but versus annual average wind speed. As annual average wind speed increases, the average difference in capacity factor between the two turbines decreases. This shows low-specific-power turbine energy production changes less than that of a high-specific-power turbine for a given change in annual average wind speed and is discussed further in Appendix B. The result of this relationship is a larger spatial footprint of technical potential from a lower specific power turbine rating, all else being equal. The scatter in the data is due to the variation in wind speed distributions at different locations. Appendix B contains additional discussion of this relationship. Roughly extrapolating, it is plausible to estimate an intersection of the data at roughly 10–11 m/s annual average wind speed, which represents the point where capacity factors for the Baseline and Innovations turbines will be equal. At 5 m/s the difference in capacity factor could be up to 50%.

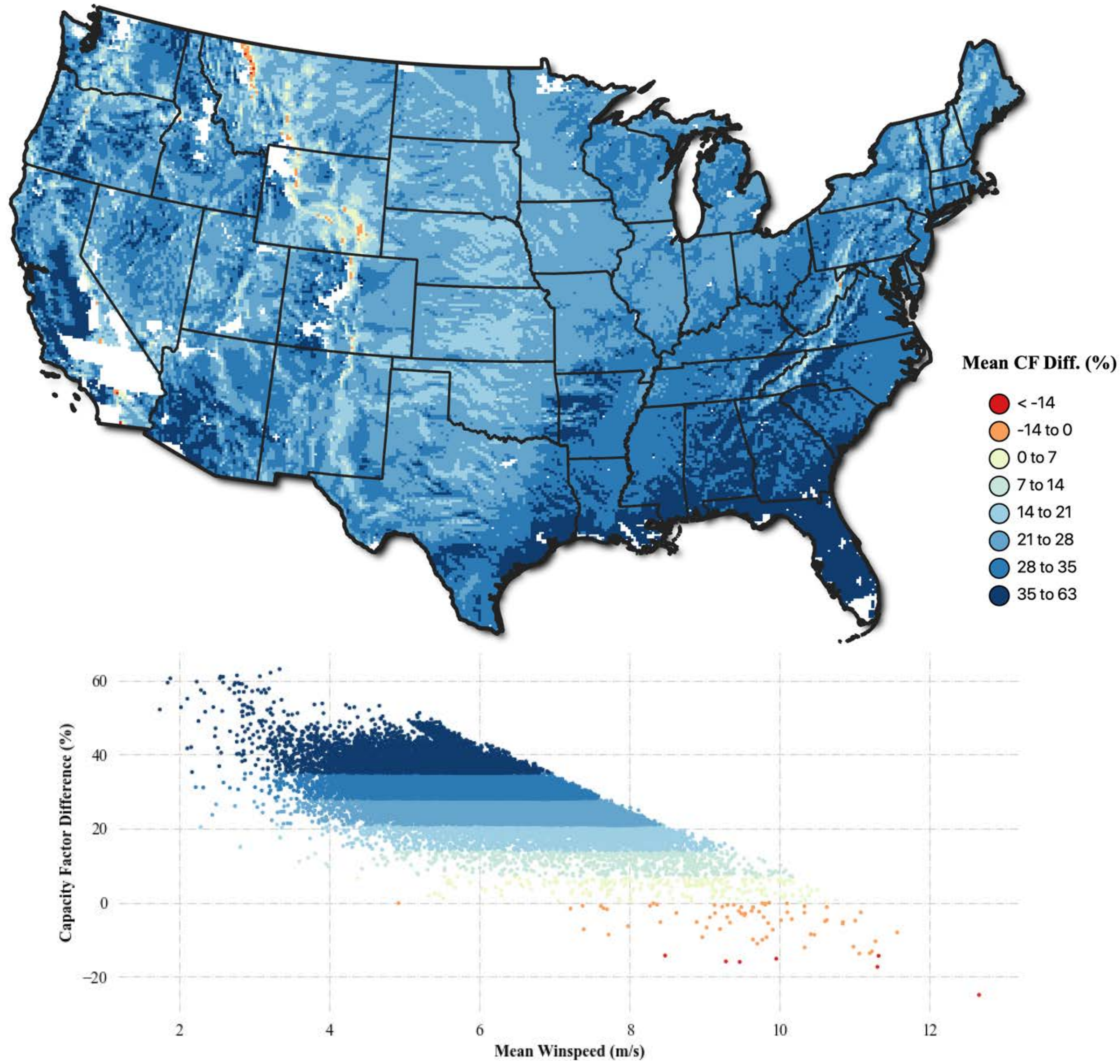

Figure 9. (a) Percent capacity factor (CF) difference between 90-m Innovations and Baseline scenarios. (b) Percent capacity factor difference between 90-m Innovations and Baseline scenarios by mean wind speed.

The selected innovations function as part of a system and can increase the cost-effectiveness of other innovations. For example, advanced towers may increase the hub height of lowest LCOE, but innovations such as up-tower O&M cranes and climbing cranes can further increase the hub height, resulting in the lowest LCOE value. Many of the innovations included in this study reduce the cost to increase hub height. However, increasing hub height also increases the setback distance from infrastructure and homes, resulting in lower technical potential capacity for a given site. Notably, in the Southeast where wind energy development is currently minimal, the Innovations turbine has 19.64% less capacity (160.6 GW) than the Baseline turbine. Figure 10 shows this difference in capacity in the Southeast region (outlined in white). Increased hub heights reduce LCOE in many locations, but increased tip heights require larger setbacks from structures and infrastructure, which reduces the number of suitable locations for wind turbines and reduces potential capacity.

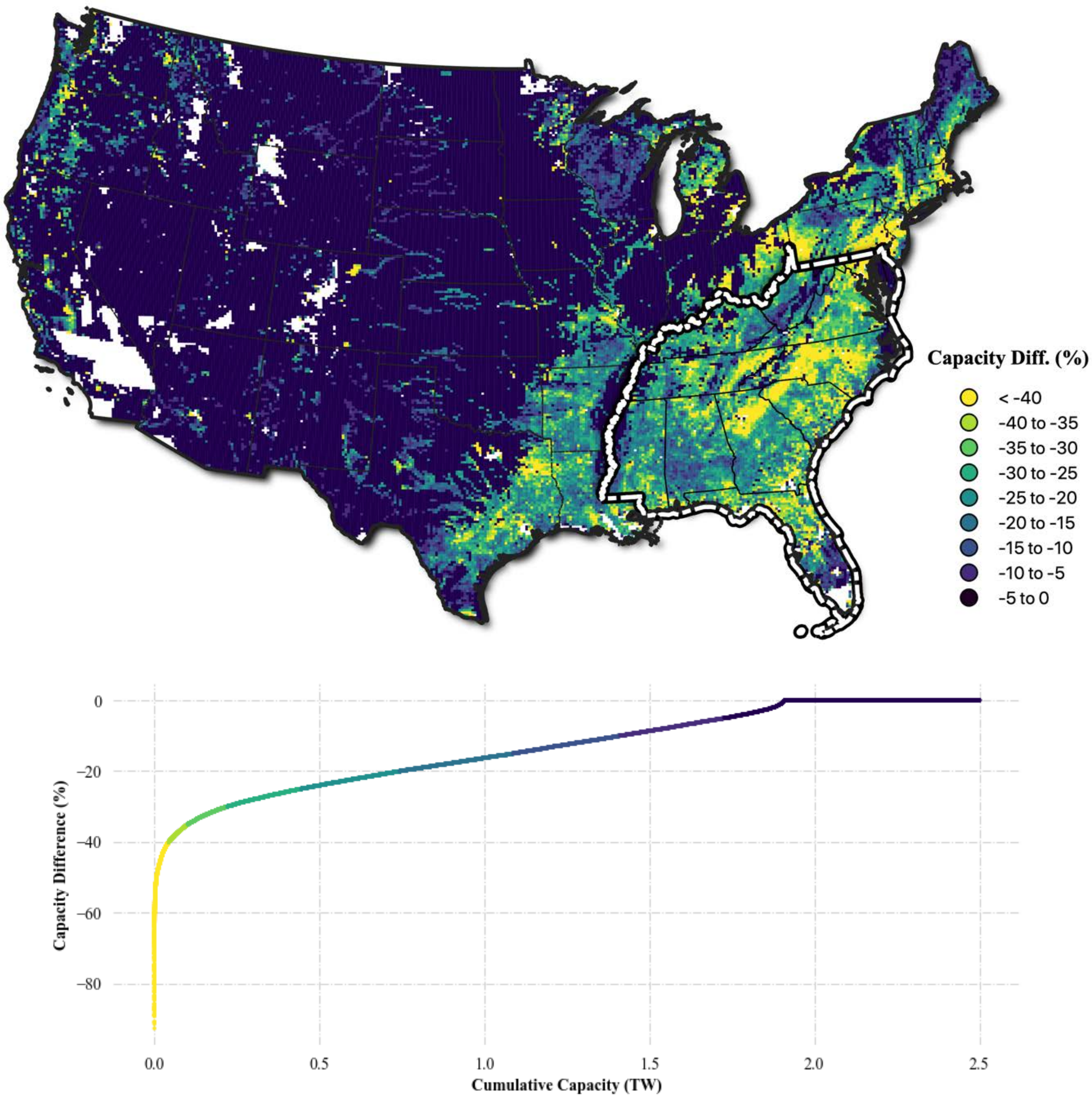

Figure 10. (a) Map and (b) cumulative capacity curve of the difference in wind farm capacity between the Innovations and Baseline turbines in the Southeast region

These innovations are planned to be commercially available in 2–5 years, as indicated by our industry partners. However, scaling of turbine rating is rapidly increasing, which may change the contributions of innovations to LCOE reduction. As turbine scaling is projected to result in turbine ratings of >5 MW by 2025 and 5–8 MW by 2030 in the United States (Barla 2021), other factors such as large O&M cost reductions (Liu 2021) may further reduce LCOE from these estimated values. However, barriers such as blade transportation logistics cost and turbine installation costs may cause specific power to increase as rating increases and LCOE values to plateau until innovations such as alternative cranes and segmented blades can enable longer blades for these higher-rating turbines (Barla 2021). Thus, the potential for innovations such as climbing cranes modeled here may increase their ability to reduce LCOE due to changes in turbine rating and/or hub height. A focus on reducing turbine installation costs and increasing blade length while reducing blade transport cost may be critical to enabling future LCOE reductions with higher turbine ratings (Barla 2021).

Cost potential is expanded to a larger area due to innovations than some projections that primarily focus on cost reductions. New potential in areas previously without significant potential may represent an increased possibility for deployment and an opportunity to meet large wind energy deployment goals. This analysis shows a significant increase in estimated cost potential in regions that currently have limited wind energy deployment. Increasing deployment of land-based wind energy in new markets will result in development and deployment hurdles that will need to be addressed. These deployment and market considerations include new siting challenges such as the need for education of communities in areas of potential deployment; new or different environmental considerations such as wildlife; siting considerations such as radar, the Federal Aviation Administration, and the U.S. Department of Defense; local ordinances; social acceptance; and others.

5 Conclusion and Future Research

Previous research showing empirical trends in wind turbine technology cost estimates, both from learning and bottom-up analyses, have pointed to increased cost potential for land-based wind energy in the United States. This report adds to such research by illustrating the change in spatial footprint due to innovations. We show that innovations, especially low specific power combined with modest cost reductions, could dramatically increase cost potential and the spatial footprint of economic potential of wind energy in the United States by 2025. Achieving ambitious goals such as 100% clean electricity by 2035 will require large amounts of land-based wind (Denholm et al. 2022), and these results show pathways to increasing the cost potential through increased spatial footprint of low-LCOE wind generation. These innovations and cost reductions could increase cost potential sooner than most projections estimate. Furthermore, a significant portion of this potential occurs in areas with little or no existing wind deployment and closer to electrical demand centers, potentially reducing the need and dependance on new transmission to deploy wind energy at the scale needed to meet renewable energy goals.

Wind energy technology innovations that are expected to be commercially available in 2 to 5 years can reduce LCOE at nearly all locations in the contiguous United States via reductions in cost, increased energy capture, and access to better resource quality. These innovations increase flexibility of national deployment spatially and could unlock about 80% more wind energy capacity, or about 2.84 TW, than can be realized under $45/MWh with 2018 baseline technology. This potential increase is most pronounced in regions with lower resource/high shear such as the East, Southeast, and Gulf Coast, where a 28% reduction in LCOE leads to about 1.23 TW of new capacity. Nationally, this expansion is associated with an average 17-m increase in hub heights. This may bring complications with siting, regulations related to aviation, and local acceptance.

These innovations may reduce dependance on new transmission due to the larger spatial footprint of cost potential. Because of the lower specific power associated with the Innovations turbines, the spatial footprint of capacity under $45/MWh expands more quickly than could be expected with industry-standard rotor diameters. Further LCOE reductions may be expected when these 2025 technologies are combined with advancements expected by 2030, resulting in even larger cost potential expansion. This places capacity closer to demand in low-resource regions and lessens the need for local governments to import energy from distant areas to meet their goals.

While recent installation trends have shown consistent reductions in specific power ratings, turbine rating scaling is reversing this trend (Wiser et al. 2021). As shown in this study, lower specific power ratings can increase the spatial footprint of cost potential. Depending on the relationship of turbine scaling and associated cost reductions, the spatial footprint of the technical potential of wind energy in the United States may be significantly different than the results presented here. Turbine technology resulting in the lowest LCOE may not be the objective of many sites, especially if sites are highly congested or "land constrained." These results do not capture the differences in turbine technologies that may be suitable for these land-constrained sites with larger, higher-specific-power turbines typically utilized as land constraints increase (General Electric 2016). Innovations enabling significantly longer blades such as segmented blades and blade transport cost reductions as well as reduced turbine installation cost scaling are required to reduce specific power ratings for current >5-MW turbines and increase the spatial footprint of cost potential.

Wind LCOE values have already fallen faster than projected, and the innovations described here have the potential to further hasten this trajectory. These results show an unexpected opportunity to utilize wind power more extensively when meeting renewable energy targets and highlights the need to communicate this potential to policymakers and other stakeholders. As deployment limitations associated with cost become less restrictive, policymakers can focus on reducing other barriers such as public knowledge of or experience with wind energy, utility experience with integrating wind and variable generation, workforce capabilities, and developer experience in regions where wind markets have not previously existed.

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Appendix A. Baseline LCOE Site Exceptions

These results reveal a handful of locations in the contiguous United States where the Baseline technology might be more cost-effective than the Innovations scenario. There are 39 such sites representing 4.1 GW, or 0.14% of the total technical potential. For example, at sites with very high wind resource, such as mountaintops, the Baseline technology LCOE was lower than the Innovations turbine Figure A-1. In such places, the performance gains from strong wind resource outweighs the cost associated with technological advancement. This is primarily driven by the cutout speed; the Baseline turbine produces power up to 25 m/s and the Innovations turbine cuts out after 18 m/s.

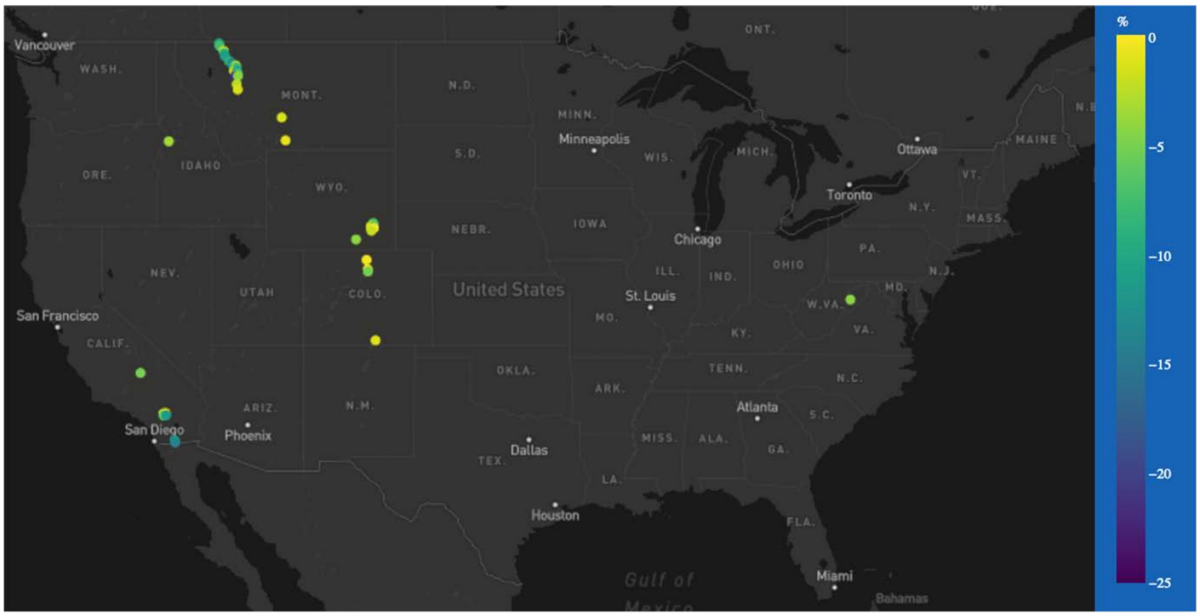

Figure A-1. Sites where the Baseline technology scenario is cheaper than the Innovations scenario. Expressed in % LCOE difference between Baseline and Innovations scenarios.

Appendix B. Low Specific Power

Figure B-1 illustrates the difference in capacity factor of wind turbines with different specific power ratings. Assuming a Weibull K factor of 2, 1.225 kg/m^3 air density, and the respective turbine power curves. Locations with a negative difference in capacity factor are sites with high annual average wind speeds with significant fractions of time where the Innovations turbine is above cutout wind speed, but the Baseline turbine is producing rated power (between 18 and 25 m/s), as illustrated in Figure B-1 for sites with annual average wind speeds greater than 10 m/s.

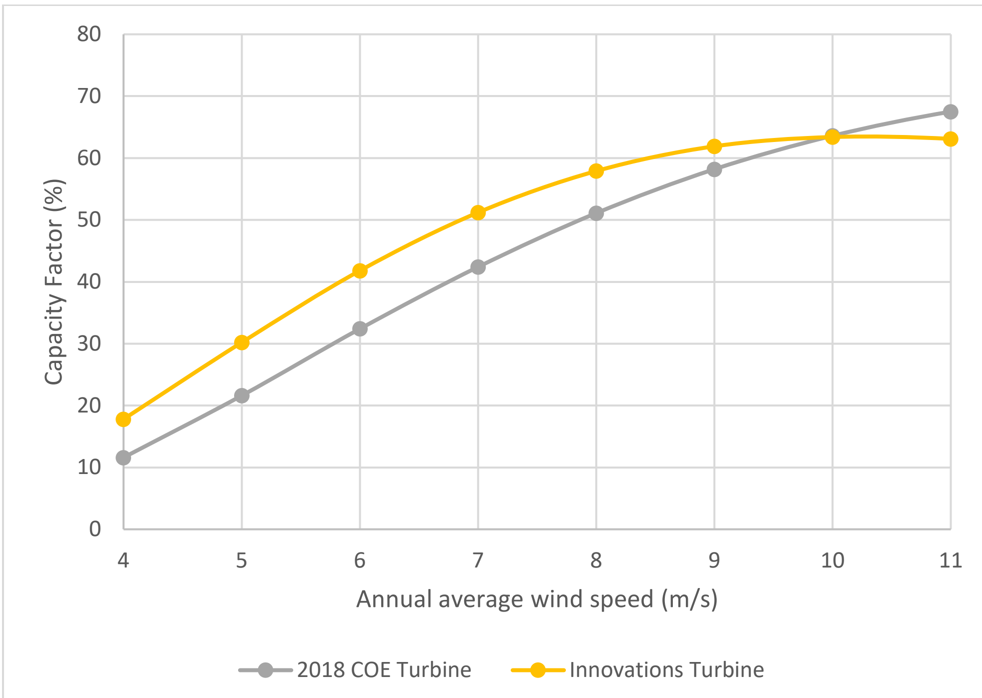

Figure B-1. Capacity factor (CF) by annual average wind speed by turbine

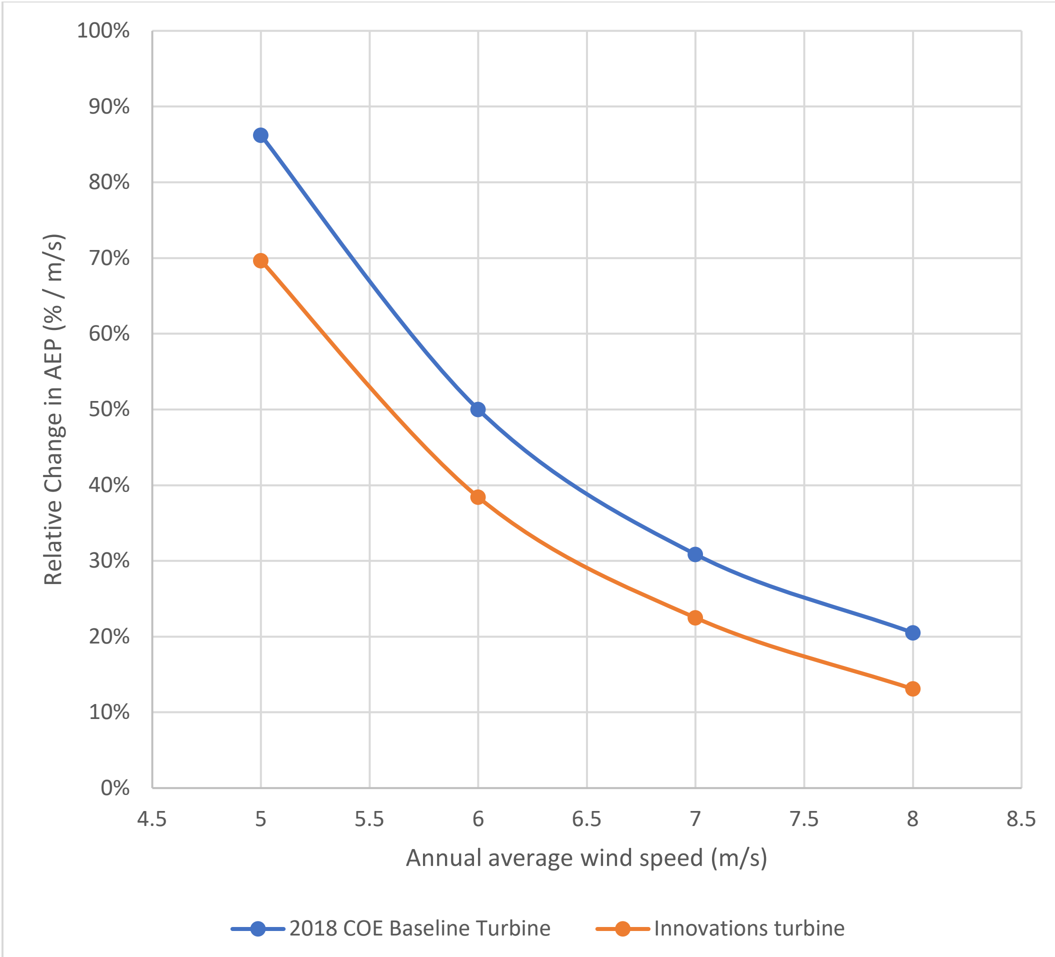

Figure B-2. Relative change in AEP per meter per second change in annual average wind speed

While the downward trend of LCOE associated with lower-specific-power turbines indicates technological advancements, turbine specific power ratings are a function of many factors. For any combination of site conditions, a specific power rating resulting in a minimum LCOE value exists. Figure B-3 shows results from the NREL Cost and Scaling Model (Fingersh, Hand, and Laxon 2006) illustrating the system-level interactions of component and installation cost scaling relationships. These results are intended to illustrate how specific power rating resulting in the minimum LCOE for each turbine rating and how the specific power rating varies by turbine rating. As component cost relationships and other cost relationships such as BOS and transportation costs vary due to innovations, changes in materials, design code, or other factors, the specific power rating resulting in the minimum LCOE value may also vary. These results do not use the same assumptions as those in this report but are meant to illustrate the cost and scaling relationships that influence the system-level minimum LCOE and resulting specific power rating.

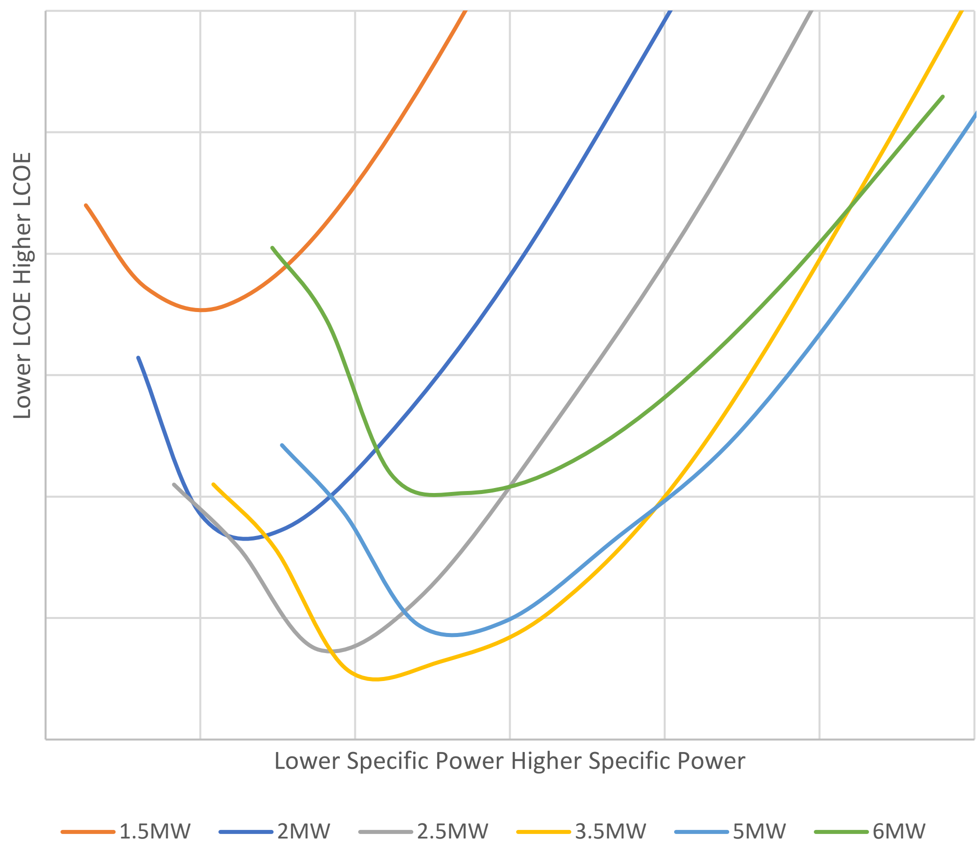

Figure B-3. LCOE by specific power by turbine rating[3]

Because lower specific power ratings produce a lower sensitivity of energy production to changes in wind speed, this same relationship applies to changes in hub height. Assuming positive wind shear, or an increase in wind speed as height above the ground increases, increasing the hub height of the turbine may be cost-effective depending on the change in cost of the tower, installation cost, magnitude of shear, wind resource, and—critically—the resulting change in energy production as a function of change in hub height. Larger changes in energy production or lower changes in cost for a change in height will increase the hub height, resulting in the lowest LCOE value for a site. For lower specific power ratings, the change in energy production for a change in hub height will be less than a higher-specific-power turbine. For any site the change in energy production will be less for a low-specific-power turbine than a high-specific-power turbine. This results in low-specific-power turbines having a lower potential contribution to changing LCOE than high-specific-power turbines.

[3] These results assume component-level scaling relationships from the Cost and Scaling Model with modifications to blade, tower, BOS, transportation costs, and other relationships. The resource is assumed to be 7 m/s annual average wind speed at 50 m above ground level with a power law shear exponent of 0.2.