Distributed Wind Energy Futures Study

Kevin McCabe, Ashreeta Prasanna, Jane Lockshin,
Parangat Bhaskar, Thomas Bowen, Ruth Baranowski,
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National Renewable Energy Laboratory

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List of Acronyms and Abbreviations

ATB	Annual Technology Baseline
CapEx	capital expenditure
C_p	coefficient of performance
DER	distributed energy resource
DOE	U.S. Department of Energy
dWind	Distributed Wind Market Demand Model (NREL)
GW	gigawatt
ITC	investment tax credit
kW	kilowatt
LRMER	long-run marginal emission rate
MW	megawatt
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PTC	production tax credit
PV	photovoltaics
TW	terawatt

Executive Summary

Wind technologies deployed as a distributed energy resource—called distributed wind—provide local, community-based, and rural energy solutions. These solutions are accessible to individuals, businesses, municipalities, and others transitioning to carbon-free electricity. Distributed wind can be placed in behind-the-meter applications, wherein the wind system provides on-site generation and directly offsets an end-user's consumption of retail electricity. Typically, these applications have a net-metering or similar electricity generation and use accounting policy in place. These systems are usually grid-connected and sized to the consumer's load. They range in size from kilowatts (kW) to megawatts (MW) and serve primarily rural or suburban homes, farms, and manufacturing facilities. Distributed wind energy may also exist in front-of-the-meter applications, wherein the system is interconnected to the distribution network and sells energy through a power purchase agreement or is owned by a local utility. These projects can involve strategic placement in the grid to bolster the robustness, reliability, and resiliency of the local distribution network and relieve transmission congestion. They may also be developed to serve the energy needs of a specific community or municipality. Front-of-the-meter applications may include multiple wind turbines greater than 100 kW in size; often, these turbines are 1 MW or larger in size.

The United States currently has the potential to profitably deploy nearly 1,400 gigawatts (GW) of distributed wind energy capacity. This amount equates to more than half of the nation's current annual electricity consumption and is enough to provide millions of American households with clean power. With favorable regulatory and policy direction, distributed wind energy could provide even more profitable power generation in the coming decades. By tapping into distributed wind's potential, the technology can supply rural homes, businesses, and communities with local clean energy resources that foster an energy transition and support the nation's low-carbon-emissions goals.

Although, rooftop solar photovoltaics (PV) provide strong head-to-head competition for distributed wind, wind and solar resources are often complementary, thereby making for compelling distributed wind, PV, and battery hybrid systems that maximize value to the energy system. In addition, distributed wind energy is relatively competitive in regions with very good wind resources and where project development, design, and construction are straightforward; for example, in simple terrain and a policy environment that is supportive for distributed wind systems. Notably, distributed wind can provide ready access to hundreds of kilowatts and megawatts with a relatively small spatial footprint, in terms of consumed land, making it attractive for space-constrained sites.

This *Distributed Wind Energy Futures Study* is an in-depth exploration of the role that distributed wind can play in the future of the nation's energy supply. In particular, the study highlights the quantities of profitable distributed wind potential today and in 2035. The study also highlights locations where distributed wind, as a local and community-based electricity resource, can be economically deployed by identifying states and counties where distributed wind is best positioned to deliver low-cost electricity to consumers and communities. This work builds on the U.S. Department of Energy's prior benchmark report, "Assessing the Future of Distributed Wind: Opportunities for Behind-the-Meter Projects" (Lantz et al. 2016), but employs higher-resolution data and new modeling techniques that provide insights for both behind- and front-of-the-meter distributed wind energy applications. The study was conducted in the context of the Biden administration's established targets of 100% carbon-free electricity supply by 2035 and net-zero greenhouse gas emissions economywide by 2050.

The study results are detailed for two snapshots in time: 2022 and 2035. The primary results are drawn from baseline conditions and the 2022 snapshot, specifically the Baseline 2022 scenario. Baseline conditions reflect policy as currently legislated and business-as-usual trends for other model input parameters. The Baseline 2022 scenario results are evaluated through the lens of economic potential and sliced by behind- and front-of-the-meter applications, land-use type, and wind turbine size. Economic potential reflects potential projects and their installed capacity that would provide a positive rate of return, or in other words be profitable, for the life of the facility. We report economic potential estimates for both 2022 and 2035 but more emphasis is focused on the 2022 results given their current market relevance. Additional scenarios focused on variability in cost and performance for large wind turbines only, financing, policy, market value for distributed energy resources (DERs), and ease of siting are explored as sensitivities to baseline conditions for the 2035 snapshot (i.e., sensitivities to the Baseline 2035 scenario). Further, for the Baseline 2035 scenario, and in the vein of the U.S. Department of Energy's Justice40 Initiative, the authors explore potential in disadvantaged communities as well as the 2035 potential of distributed wind energy to offset carbon emissions.

Key findings from our work include the following:

- **The opportunity for distributed wind is substantial, with nearly 1,400 GW of economic potential today. With the potential for several terawatts (TW) more of profitable wind generation by 2035, distributed wind energy can be a significant contributor to the nation's electricity supply.** However, it is important to note that economic potential—which here simply reflects profitability given specific benchmark costs—is a necessary but not sufficient condition to drive widespread deployment of distributed wind energy systems. Increasing competitiveness with other distributed energy resources through lower costs and driving down life cycle risks and customer acquisition costs are also important to foster customer uptake and use.
- **Economic potential is higher for behind-the-meter applications, at 919 GW, with 474 GW for front-of-the-meter applications in the Baseline 2022 scenario. However, with future policy support and more relaxed siting conditions, the economic potential of front-of-the-meter applications increases to more than 4 TW in our Optimistic 2035 scenario, as compared to approximately 1.7 TW for behind-the-meter applications.** These results demonstrate the relative near-term economic opportunity that comes with offsetting retail rates for behind-the-meter applications as well as the extensive longer-term potential for front-of-the-meter applications to provide community-based wholesale power and to support the distribution system in windy locations across the country.
- **Economic potential for behind-the-meter distributed wind applications in the Baseline 2022 scenario is deepest in the Midwest and heartland, with approximately 500 GW in the top six states alone. These states include Texas, Minnesota, Montana, Colorado, Oklahoma, and Indiana.** Focusing on development opportunities in these states would provide a large pool of economically viable projects to consider. More generally, behind-the-meter opportunities are compelling in sites that possess a combination of windy land and

higher retail electricity rates. As a result, favorable conditions also exist in pockets of the Pacific and Northeast regions.

- **Economic potential for front-of-the-meter distributed wind in the Baseline 2022 scenario is also deepest in the Midwest and heartland with over 300 GW in the top six states. These states include Oklahoma, Nebraska, Illinois, Kansas, Iowa, and South Dakota.** Focusing on development opportunities in these states would similarly provide a large pool of economically viable projects to consider. Without the same strong correlation with retail rates that accrues for behind-the-meter distributed wind, front-of-the-meter opportunities tend to be most correlated with wind resource quality.
- **Agricultural lands make up 70% of the total 2022 economic potential for behind-the-meter wind and 97% of the total 2022 economic potential for front-of-the-meter wind. Focusing on the top six states alone, the economic potential on agricultural lands is more than 400 GW for behind-the-meter wind and more than 300 GW for front of the meter.** These results demonstrate the sizable economic potential available on agricultural lands in the heartland today as well as significant opportunities for agricultural decarbonization and revenue diversification.
- **Kansas, Colorado, Texas, South Dakota, New Mexico, and Kentucky each have more than 900 MW of behind-the-meter economic potential in 2022 on commercial and industrial lands.** Front-of-the-meter technical potential on commercial and industrial lands is calculated to be hundreds of gigawatts, but significant economic potential was not identified. These results demonstrate that the near-term potential for behind-the-meter systems on commercial and industrial lands is significant at the gigawatt scale. Overall, commercial and industrial lands make up significantly less area than agricultural land, but still offer compelling near- and long-term distributed wind energy potential, particularly for behind-the-meter applications.
- **Behind-the-meter economic potential in 2022 on residential lands is largest in New York, Minnesota, Kentucky, Texas, Oklahoma, and South Dakota.** In addition, based on the combination of windy land and relatively higher retail electricity rates, some states like Minnesota, California, and Massachusetts have locations with especially high threshold capital expenditure (CapEx) values. Threshold CapEx is an indicator of the amount of capital that could be invested for a system at a specific site while still maintaining profitability; higher threshold CapEx values mean higher favorability for distributed wind energy. Given their high threshold CapEx values, these states have regions worth exploring further for their potential for near-term projects. No significant economic potential was identified for front-of-the-meter wind on residential lands and in practice these project types are unlikely to be a major market component, at least for the foreseeable future.
- **Economic potential for 2022 for residential-sized wind turbines (<20 kW) in behind-the-meter applications is more than 40 GW in each in the top 10 states. Economic potential in 2022 for commercial-sized wind turbines (20 to 100 kW) in behind-the-meter applications ranges from 100 MW to more than 7 GW in Colorado (the top state), indicating a smaller but still significant market for commercial-sized turbines.** Residential- and commercial-sized wind turbines were not observed and are not expected at significant levels for front-of-the-meter applications. Overall geographic distribution of

economic potential by turbine size correlates strongly with the broader trends in economic potential.

- **Today's 2022 economic potential for midsize and large turbines (100 kW to multimegawatts) is largest for behind-the-meter applications in Massachusetts, Ohio, Texas, and Kansas, with each state having several hundred megawatt-to-gigawatt levels of potential; front-of-the-meter applications are best for this size class in Oklahoma, Nebraska, Illinois, Kansas, Iowa, and South Dakota, where each state has more than 30 GW of economic potential.** Close examination of states and counties where midsize and large turbines have significant potential in behind- and front-of-the-meter systems could yield new opportunities for deployment.
- **If current tax credits and net-metering policies expire as scheduled, economic potential drops between 2022 and 2035. However, if current tax credits and policies are extended and strategically expanded, economic potential increases by more than 80% for behind-the-meter applications and by a factor of nearly nine for front-of-the-meter applications.** Accordingly, the economics of distributed wind and the role it might play in the future energy system are particularly sensitive to policies, especially those that impact project-level costs. Given competition between DERs, including wind and solar, close examination and analysis of proposed policy provisions and their applicability to distributed wind is important if stakeholders seek to convert distributed wind energy's potential into deployment.
- **Economic potential is sensitive to siting considerations when the economics of distributed wind energy are favorable.** In our 2035 scenarios, changing siting requirements primarily impacts technical rather than economic potential, unless the cost or value of distributed systems is also varied. When conditions are ripe for distributed wind energy, siting barriers can prevent otherwise viable projects from moving forward. On the other hand, if the economics of distributed wind are challenging, efforts to support distributed wind would do well to prioritize siting in concert with complementary actions that enhance overall competitiveness.
- **Changing operations, maintenance, and performance assumptions for large wind turbines only more than doubles front-of-the-meter 2035 economic potential, increasing it from 160 GW to 342 GW.** Impacts on behind-the-meter applications are not significant due to scenario design which focused the changes on large turbines only.
- **Changes in the market value of DERs in 2035 as modeled here drive a slight decrease in behind-the-meter potential and a 96 GW (60%) increase in front-of-the-meter economic potential.** This may be, in part, a result of the sizable behind-the-meter potential that is present even under baseline conditions or perhaps lack of sufficient resolution in our modeling approach to illuminate potential effects from changes in the market value of DERs, particularly for behind-the-meter potential.
- **Our 2035 financing scenario sensitivity increases behind-the-meter potential by 211 GW (27%) and front-of-the-meter potential by 353 GW (221%).** This suggests that access to low-cost financing or other forms of financing support could have a significant effect on economic viability and ultimately, the potential for both behind- and front-of-the-meter distributed wind applications.

- **In 2022, the top six states with the highest economic potential for front-of-the-meter distributed wind energy in disadvantaged communities total more than 120 GW and include Oklahoma, Illinois, Kansas, New Mexico, Nebraska, and Montana. The top six states with the highest economic potential for behind-the-meter distributed wind energy in disadvantaged communities total more than 200 GW and include Texas, Montana, New Mexico, California, South Dakota, and Kansas.** Based on their distribution and frequency across the country there is strong correlation between favorable states for distributed wind and disadvantaged communities. This is particularly true in the Midwest and Heartland but includes coastal regions with high threshold CapEx values. Based on these outcomes, locations where distributed wind could provide energy and environmental benefits to rural and remote disadvantaged communities are likely abundant.
- **Montana, North Dakota, Kansas, Oklahoma, and Nebraska display higher emissions offset potential at 3,000 to 5000 metric tons per year for front-of-the-meter applications and reflect the favorable intersection of good wind resource and high long run marginal emissions rates.** The magnitude of these offset emissions estimates is relatively large compared to the behind-the-meter wind values due to the larger average wind system size that is observed for front-of-the-meter applications as well as stricter siting restrictions (e.g., consumer load and parcel size) for behind-the-meter applications. Higher emissions offset potential for behind-the-meter applications are shown in Kentucky, North Carolina, Indiana, Utah, and Rhode Island with levels of 15 to 27 metric tons per year in these states.

Overall, the potential for distributed wind energy is significant both today and into the future, providing profitable pathways to clean energy futures for homes, businesses, municipalities, and communities. Moreover, by reducing reliance on the nation's already constrained transmission network, distributed wind can foster clean energy development in parallel with transmission expansion. These opportunities may be even more compelling when these systems are combined with solar and batteries to maximize their value to the grid. Given strong economics, focused efforts could foster deployment across the nation, providing a compelling motivation for continued work to enhance distributed wind energy's competitiveness with other distributed energy resources and to increase its attractiveness for consumers as an energy technology serving both end users and communities in realizing their ambitions for low-cost, abundant clean energy.

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1 Introduction

The modern electricity system is changing. In 2020, renewable energy sources accounted for approximately 19.8% of electricity generation (U.S. Energy Information Administration 2021). Investors and developers continue to pursue opportunities for new wind and solar projects as well as so-called "hybrid" facilities combining multiple forms of generation and storage to maximize grid value and associated revenue. In this context, the Biden administration has ambitions for a 100% clean electricity sector by 2035 and a net-zero carbon economy by 2050 (The White House 2021). At these scales and pace, every available cost-effective option for renewable power needs to be explored with goals of sufficiency and diversity in energy supply. Generation sources will also likely span from the residential to the utility scale, inclusive of local- and community-focused energy resources. The transition to a clean energy future is also a major opportunity to realize the economic benefits of large-scale clean energy deployment, including growing U.S. manufacturing, the supply chain, and a skilled workforce.

Wind technologies deployed as a distributed energy resource—called distributed wind—provide local, community-based, and rural energy solutions. These solutions are accessible to individuals, businesses, municipalities, and others transitioning to carbon-free electricity. Distributed wind can be placed in behind-the-meter applications, wherein the wind system provides on-site generation and directly offsets an end-user's consumption of retail electricity. Typically, these applications have a net-metering or similar electricity generation and use accounting policy in place. These systems are usually grid-connected and sized to the consumer's load. They range in size from kilowatts (kW) to megawatts (MW) and serve primarily rural or suburban homes, farms, and manufacturing facilities. Distributed wind energy may also exist in front-of-the-meter applications, wherein the system is interconnected to the distribution network and sells energy through a power purchase agreement or is owned by a local utility. These projects can involve strategic placement in the grid to bolster the robustness, reliability, and resiliency of the local distribution network and relieve transmission congestion. They may also be developed to serve the energy needs of a specific community or municipality. Front-of-the-meter applications may include multiple wind turbines greater than 100 kW in size; often these turbines are 1 MW or larger.

In 2016, a team of researchers at the National Renewable Energy Laboratory (NREL) published *Assessing the Future of Distributed Wind: Opportunities for Behind-the-Meter Projects* (Lantz et al. 2016). This first-of-a-kind exploratory analysis characterized the future opportunity for grid-connected, behind-the-meter distributed wind. The report focused only on the behind-the-meter subset of the broader distributed wind energy market and found that there is both a large resource and conditions under which the economics for large quantities of distributed wind become viable over time, suggesting the possibility for a robust future.

In this 2022 report, researchers build on the foundation established in the 2016 analysis, employing higher-resolution data and new modeling techniques to characterize the favorability of counties, states, and regions to distributed wind energy deployment. Further, the analysis has been extended to characterize the potential of front-of-the-meter distributed wind and to explore the sector from multiple perspectives including opportunities for disadvantaged communities.[1] Front-of-the-meter applications are of interest based on their ability to increase grid reliability and resilience, and to enable communities to use local resources to serve their electricity needs. Notably, a total of 45% of all documented U.S. distributed wind capacity from 2010 through 2020 provides electricity for behind-the-meter use, whereas 55% provides electricity for front-of-the-meter use (Orrell, Kazimierczuk, and Sheridan 2021). Although we consider front-of-the-meter opportunities, inclusive of projects designed to provide local energy for communities or municipalities, we did not study community ownership models (e.g., by local governments, co-ops, or community organizations) or financing mechanisms. The drivers and financial structures of community ownership are varied and nuanced and in general beyond the scope of the variables modeled as part of this 2022 analysis.

Notably, rooftop solar photovoltaics (PV) provide strong head-to-head competition for distributed wind. This report focuses predominantly on potential for distributed wind energy and does not make direct comparisons between the technologies. We do, however, include limited discussion of the PV potential, for the same scenarios we report on for wind in Appendix E. Moreover, we observed that wind and solar resources are often complementary, making for compelling distributed wind, PV, and battery hybrid systems that help maximize value to the energy system. Generally, distributed wind energy is relatively competitive in regions with very good wind resources and where project development, design, and construction are straightforward; for example, in simple terrain and a policy environment that is supportive for distributed wind systems. Distributed wind can also provide ready access to hundreds of kilowatts and megawatts, with a relatively small spatial footprint–in terms of consumed land–making it attractive for space-constrained sites as well.

1.1 U.S. Distributed Wind Energy Overview

The distributed wind energy industry, like the greater U.S. wind energy industry, has grown in the past 7 years. By 2015, total U.S. installed wind capacity had reached 73,992 MW (Wiser and Bolinger 2016). The 2016 futures study reported that cumulative distributed wind installations through 2015 totaled 934 MW (Lantz et al. 2016). In 2020, the cumulative total U.S. wind capacity reached 121,955 MW (Wiser et al. 2021). Cumulative U.S. distributed wind capacity installed through 2020 reached 1,055 MW from approximately 87,000 wind turbines across all 50 states, Puerto Rico, the U.S. Virgin Islands, and Guam (Orrell, Kazimierczuk, and Sheridan 2021), an increase of 121 MW from the 2016 reported figures. Of the 14.7 MW of distributed wind capacity installed in 2020, 12.9 MW came from projects using large-scale wind turbines (greater than 1 MW in size), 0.16 MW came from projects using midsize turbines (101 kW to 1 MW in size), and 1.6 MW came from projects using small wind turbines (up through 100 kW in size) (Orrell, Kazimierczuk, and Sheridan 2021).

[1] The U.S. Department of Energy's Office of Economic Impact and Diversity defines a disadvantaged community as a group of individuals experiencing low income and high and/or persistent poverty; high unemployment and underemployment; racial and ethnic segregation; linguistic isolation; high housing cost burden and substandard housing; distressed neighborhoods; high transportation cost burden and/or limited transportation access; disproportionate environmental stressor burdens and high cumulative impacts; limited water and sanitation access and affordability; disproportionate impacts from climate change; high energy cost burden and low energy access; jobs lost through the energy transition; or limited access to healthcare.

In 2015, the top five states for distributed wind capacity were Texas, Minnesota, Iowa, California, and Massachusetts (Orrell and Foster 2016). In 2020, the top five states were the same, but the ranking order changed to Iowa, Minnesota, Massachusetts, California, and Texas, largely the result of two large projects installed in Iowa and Minnesota (Pacific Northwest National Laboratory n.d.). In 2020, new distributed wind energy projects were reported in the following 11 states: California, Colorado, Iowa, Minnesota, Montana, New Jersey, New York, North Carolina, Ohio, Texas, and Wisconsin (Orrell, Kazimierczuk, and Sheridan 2021).

Distributed wind customer types in the United States include utility, residential, institutional, government, commercial, industrial, and agricultural. Figure 1 provides an overview of the percentage of *total capacity* of distributed wind energy projects by customer types. On this basis, utility and industrial consumers are the predominant customer types. In contrast to these data, when assessed by *number of projects*, agricultural and residential end-use customers represent most of the distributed wind installations. Despite their relative frequency, these customer types constitute relatively less market share by capacity because of the smaller wind turbines they typically use (Orrell, Kazimierczuk, and Sheridan 2021).

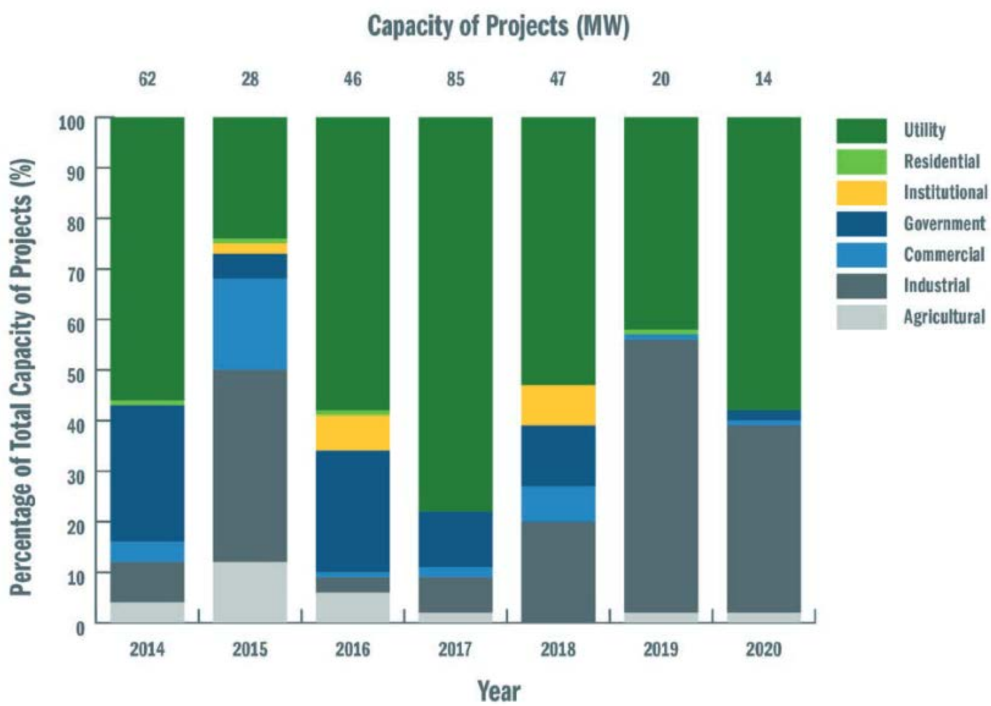


Figure 1. Capacity of distributed wind energy projects (2014–2020) by end-use customer types.
Image from Orrell et al. (2021)

1.2 Distributed Wind Energy Potential in the United States

The U.S. Department of Energy's (DOE's) *Distributed Wind Market Report 2021 Edition* reported that the U.S. small wind market (typically 0–100 kW applications) has been steadily declining since a 2012 peak due to increasing competition from the falling cost of solar PV and eroding policy support. However, it also reported that during 2021 small wind manufacturers and installers held a brighter outlook for the future, attributing "the role that distributed energy resources can play in addressing energy security, grid resilience, and climate change challenges" (Orrell, Kazimierczuk, and Sheridan 2021).

As a complement to this optimism, our analysis provides current insights based on granular land use characteristics to illuminate the best locations for distributed wind energy in all forms and highlights the favorability of counties, states, and regions (see Section 4 for a complete discussion of results). Our scenarios indicate abundant, terawatt-scale economic potential. However, it is important to note that delivering a profitable project may not position distributed wind as the lowest-cost distributed energy solution. Further, ultimate market potential will be determined by the industry's ability to drive down life cycle risk and attract customers who may not understand the economic potential of the technology. In this vein, cost-effectiveness, including the ability to compete with other distributed energy resources, and therefore future potential of distributed wind energy is highly dependent on key variables including policy support, the compensated value of distributed generation (including future net-metering policies), financing costs and risks, turbine performance, and siting restrictions. Continued work analyzing and understanding each of these domains will be important for a robust distributed wind energy future.

1.3 Distributed Wind-PV Complementarity

This report includes data and analysis that inform potential for both distributed wind and solar PV generation (see Appendix E for PV results). Distributed wind turbines and solar PV systems are both distributed energy resources that can be connected at the lower-voltage distribution level of the electricity grid to serve specific or local loads. In some instances, these technologies may compete head-to-head to provide electricity for a distributed load. However, in other instances, wind and PV, sometimes coupled with batteries, offer complementary solutions for the supply of clean electricity in distributed applications.

Complementarity exists in many specific locations around the contiguous United States (Clark et al. 2022), as well as between regions (Ramdas et al. 2019). In simple terms, for a given location, complementarity is high when different resources (e.g., wind and solar) generate electricity at different times of the day. The simplest example is when it is sunny in the day and windy at night. Complementarity is lower if the generation sources are generating at the similar times, potentially creating periods of too much and too little electricity and increasing the challenge of serving consumption patterns. Between regions complementarity may exist for the same or different resources, as long as they are generating at different times and the grid network allows for electricity exchange. In co-located systems, complementarity is relatively focused on the combined (e.g., wind and solar) generation profile for a given site. A complementary generation profile is one that is ultimately of higher value for the facility, as compared to only one generation technology. Often these co-located applications can be optimized to make the best use of the available land, interconnection capacity, and permitting processes to provide additional cost savings and value to the project sponsor.

To better understand co-located complementarity, Clark et al. (2022) studied seasonal (i.e., summer and winter) and diurnal (i.e., morning and night) patterns in wind and solar profiles across the contiguous United States. Clark et al. (2022) used the Pearson coefficient to illustrate sites and regions where the combined wind and solar profiles were complementary. In this approach, a positive value shown by the blue color in Figure 2 means that the generation of each resource type (wind and solar) occurs at the same time. A value of +1 indicates that the generation is occurring at precisely the same time. In these instances, the sites are not complementary. In contrast, a negative value (red in Figure 2) means the generation from each resource is occurring at different times, making the resources complementary. A value of -1 indicates that the generation profiles are the inverse of each other, effectively minimizing the peaks and valleys that might be present in the generation profile of wind and solar for that site. Figure 2 shows that regions in the Great Plains, Midwest, and Southeast are particularly suited for hybrid power plants consisting of co-located wind and solar generation. Their results also indicate that the pairing of wind and solar energy assets better serves supply and demand balancing and reduces storage requirements compared with using only solar assets (Clark et al. 2022). Although we emphasize distributed wind energy results and opportunities in our work, a summary of key results for PV for the same scenarios and metrics is available in Appendix E.

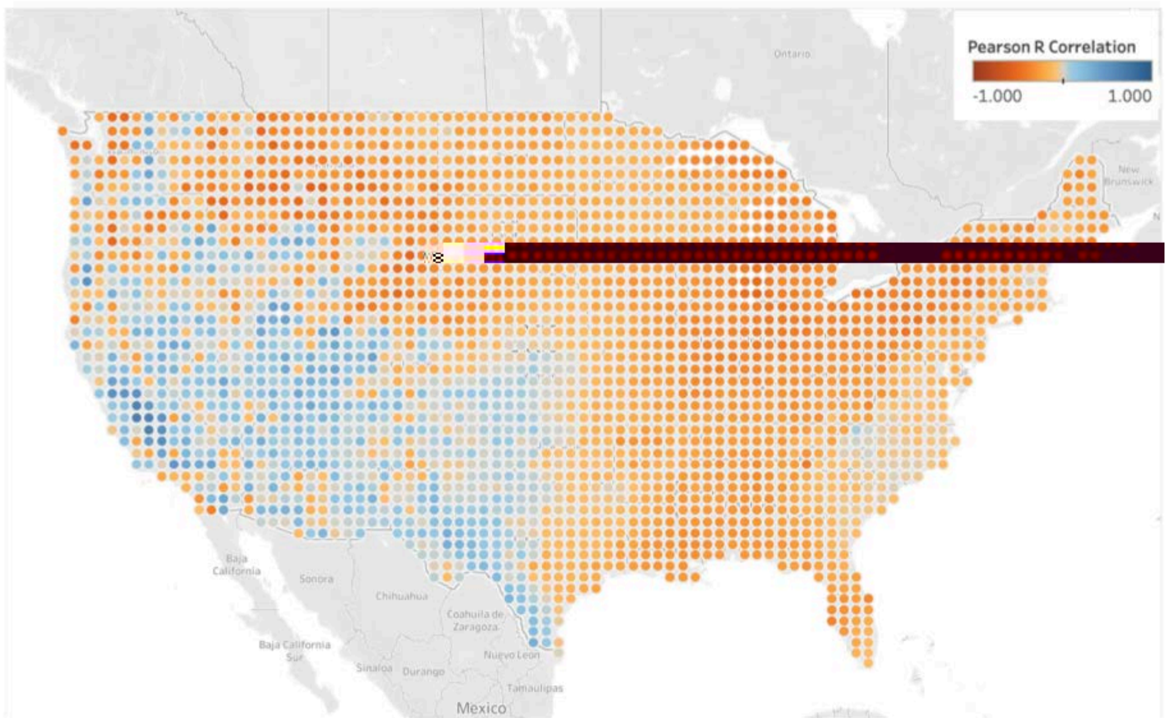


Figure 2. Annual, daily-averaged complementarity (represented by the Pearson correlation metric) for 2013 in the contiguous United States. Sites with good complementarity (red) tend to be in the east and Great Plains; sites with correlated generation (blue) are not complementary and occur more often in the Southwest and West. ***Image from Clark et al. (2022)***

Note: A negative value reflects complementary sites; a value of -1 indicates inverse generation profiles. A positive value reflects correlated sites or locations where wind and solar generation occurs at the same time; a value of +1 indicates the generation occurs at precisely the same time.

1.4 Distributed Wind and Energy Equity Considerations, Considering Rural and Remote Communities

Along with our core results and scenarios, this report includes a basic assessment of energy equity considerations and the intersection with distributed wind energy potential (See Section 5 and Appendix F). Namely, we examine the opportunities for distributed wind energy in both disadvantaged and other communities, to explore how investing in distributed wind might contribute to the Biden administration's Justice40 Initiative. The initiative sets a goal that 40% of the overall benefits of certain federal investments—including investments in clean energy, training, and workforce development—flow to disadvantaged communities and inform equitable research, development, and deployment (DOE 2022a). Notably, private industry also supports energy equity considerations. In July 2020, the Distributed Wind Energy Association issued a statement in support of energy justice with ideas for specific near-term actions that distributed wind industry members can take to support equity (Distributed Wind Energy Association 2020).

To incorporate equitable research into this 2022 *Distributed Wind Energy Futures Study*, we specifically include an analysis of opportunities in disadvantaged communities. In principle, these opportunities could serve as a means of alleviating energy burden, which is defined as the amount of household income spent on energy services.

In addition, The Bipartisan Infrastructure Law of 2022 provided a provision for "Energy Improvement in Rural and Remote Areas" for financial assistance to increase environmental protection from the impacts of energy use and improve resilience, reliability, safety, and availability of energy in rural or remote areas of the United States (DOE 2022b). Focusing on increasing the cost-effectiveness of energy generation, strengthening energy infrastructure, and reducing greenhouse gas emissions from energy generation in these communities, the provisions of this law provide investment in local infrastructure for these communities. As is demonstrated through this report, the overlap for potential distributed wind development and rural communities is quite large, indicating the possibility for this provision of the Bipartisan Infrastructure Law to support the expanded demonstration distributed wind in support remote and rural community development.

1.5 Report Organization

This report characterizes the potential for distributed wind energy—behind-the-meter and front-of-the-meter projects—in the United States. Section 2 provides a discussion of the dWind model and advancements in the capabilities made to it since the 2016 study. Section 2 also discusses the threshold capital expenditure (CapEx), the primary metric used in the study. Section 3 describes the full suite of scenarios analyzed. Specifically, it discusses the two baseline scenarios developed as part of this analysis—one for 2022 and another for 2035—and the additional scenarios that build on these baselines. Section 4 presents the results of the analysis across multiple dimensions: the cost-effectiveness of distributed wind energy under selected scenarios, regions, and sectors where opportunities for distributed wind exist, and the potential for distributed wind in disadvantaged communities. Section 5 covers the potential for distributed wind to support decarbonization of the electricity grid. Section 6 concludes with a discussion of the results as well as opportunities for future capability advancements and analysis opportunities.

We discuss a fully elaborated methodology of the study in Appendix A, including the constraints on where systems are sited, how they are sized, how an optimal system is selected based on factors like the parcel attributes, the resource potential of a site, the technology specifications (e.g., hub height, maximum blade tip height), and the compensation mechanisms or revenue streams applicable in that region. Additional appendices cover the model workflow; technology cost and performance assumptions; data and mapping; sensitivities; energy equity indices; parcel data attributes; and distributed solar results.

Note that in this report we frequently use the term “parcel.” Here, a parcel refers to a parcel of land or a quantity of land that is owned and documented in the property tax system. In some cases, single entities may own multiple adjoining parcels, resulting in a situation where multiple parcels make up a given landowner’s property boundaries. Parcels considered in this study may be well below one acre or tens of acres, depending on the location, land-use type, historical patterns of ownership, and subdivision.

2 Model and Methodological Improvements

NREL's work in distributed wind energy potential, including prior efforts by Lantz et al. (2016) and this 2022 study, were conducted with NREL's dWind model (Sigrin et al. 2016). The dWind model is part of NREL's Distributed Generation Market Demand (dGen™) suite[2] of distributed generation technology diffusion models. dWind evaluates the resource, economics, siting, load, and policy conditions for millions of potential distributed wind sites across the nation. The model provides an internally consistent framework for understanding and characterizing potential future scenarios as a function of the modeled inputs. Model results are not intended as forecasts.

2.1 Model Background

Broadly, the dGen and dWind model capabilities reflect an agent-based and geospatially rich characterization of the core variables of relevance to distributed energy resources (DERs) and technologies including consumers; applicable policy and retail rate provisions; and renewable energy resource and system potential.[3] In the dGen and dWind models, the "agents" are representative customers. "Geospatially rich" describes the relatively high degree of spatial resolution that is applied in the model and informs our results. Using these data, the model characterizes the technical potential for DER systems and simulates the economic potential for millions of DER systems around the continental United States. For those studies that are focused on technology adoption, consumer behavior is also considered. Collectively, the model data and characteristics allow us to analyze potential and demand for various distributed energy resources including wind, solar, batteries, and others. The following five steps are part of dGen modeling, adapted from Sigrin et al. (2016):

1. Generate the agents (customers) and characterize their potential for DERs, including electricity demand and applicable electricity rates policies

2. Apply siting restrictions and determine what size system might be feasible for a given agent

3. Perform economic calculations using discounted cash flow analysis and the applicable costs and revenue streams for a given agent

4. Calculate market share based on the assumed technology adoption trends

5. Generate output data and results that display the sizes, types, and locations among other parameters for the simulated systems.

Among these five steps, this study relies on 1, 2, 3, and 5 to illuminate technical and economic potential for distributed wind energy technologies. Step 4, where adoption is considered, was not within the scope of this analysis. Relative to Lantz et al. (2016), model advancements have focused heavily on Steps 1 and 2. We also include a new economic metric, "threshold CapEx," and have added capabilities to assess front-of-the-meter applications, which rely on much of the same geospatial data but include additional wholesale power price data and eliminate wind

[2] https://www.nrel.gov/analysis/dgen/

[3] Sigrin et al. (2016) provides a detailed overview of the dGen modeling capabilities. Sigrin et al. (2016) and Lantz et al. (2016) describe many of the foundational elements of distributed wind technology representation in the model.

turbine sizing constraints imposed by customer load. The relevant model advancements, as well as their impacts on the model workflow for this study, are described in greater detail in the following sections.

2.2 Model and Capability Advancements

In the current application of the dWind model, we leveraged several new data sources and enhanced capabilities. Most notably, a property-tax, system-derived, land parcel data set containing more than 150 million parcels of land enables detailed analysis of trends by land-use type, end-use sector, and geography in urban and suburban settings. We implemented these data in the model so that each agent is represented at the parcel level. These advancements allow the model to produce robust estimates at a finer spatial resolution than was previously available and to leverage detailed parcel-level attributes, such as building information and land-use types (see Appendix A).

Although the original dWind model was limited to analyzing only behind-the-meter systems, the latest iteration is now capable of modeling front-of-the-meter systems. This new capability is made possible primarily by Cambium (Gagnon et al. 2020), a tool that assembles structured data sets of simulated hourly emission, cost, and operations data to provide insight into the future operation of the U.S. electric sector and the associated value streams.[4] Our model uses several of these data sets as key inputs that inform analysis of front-of-the-meter systems. Cambium provides hourly data for marginal capacity and energy costs that are used as available revenues to front-of-the-meter systems. Cambium also provides several emissions metrics, such as the long-run marginal emission rate (LRMER), which help analyze the decarbonization potential of distributed wind energy systems. Appendix A provides a detailed discussion of Cambium and these outputs.

In addition, the dWind model now assesses technical potential via a direct integration with NREL's Renewable Energy Potential (reV) tool, which calculates the capacity, generation, and cost of wind and solar PV systems based on the site's resource potential and land-use constraints. This tool relies on high-resolution geospatial data from the National Solar Radiation Database and the Wind Integration National Dataset (WIND) Toolkit to model the system performance of distributed wind and solar PV at subhourly intervals.[5]

Distributed generation is modeled using PySAM, the Python wrapper of NREL's System Advisor Model (SAM), which offers detailed models of wind and solar PV systems.[6] The integration of PySAM represents a significant upgrade, as it provides the ability to model complex cashflow analysis and retail tariff representation in addition to providing support for new compensation mechanisms for behind-the-meter systems, such as variable rates for net billing. Detailed analysis of front-of-the-meter systems is also enabled by integrating PySAM via the Merchant Plant financial model, which enables specification of market prices that can vary on an hourly basis.

[4] See https://www.nrel.gov/analysis/reeds/ and https://www.nrel.gov/analysis/cambium.html.
[5] See https://www.nrel.gov/gis/renewable-energy-potential.html.
[6] See https://sam.nrel.gov/software-development-kit-sdk/pysam.html.

Finally, the underlying cost and performance specifications have been updated to align with contemporary data sources on the current and future trajectories of wind and solar characteristics. We have integrated updated data on costs (e.g., CapEx, operations and maintenance [O&M]), technology performance (e.g., PV panel efficiency, wind turbine power curves), and financing parameters (e.g., discount rate, interest rate). For solar, these data for both behind-the-meter and front-of-the-meter applications are readily available via NREL's Annual Technology Baseline (ATB) (NREL 2020). Data for utility-scale wind is also available via the NREL ATB; however, no such centralized data source exists for distributed wind.[7] Appendix B details our efforts to characterize current and future cost and performance parameters for distributed wind energy.

2.3 Model Workflow

This section describes how we performed a model run and the order of operations (Figure 3). It also features visual examples of two parcels that illustrate the various geographical layers and associated boundaries that comprise the parcel data set and highlight the fine geospatial resolution that underpins the parcel-level modeling capabilities developed for this study. While a general overview of the model workflow is given here, Appendix A provides more details on the methodology of the study and the high-level steps discussed in this section.

The first step involves sampling parcels from the full parcel data set. The final sample only included parcels located in the contiguous United States and those that have available land-use information. The need for sampling is because of the large size of the full data set (more than 150 million entries) and the associated computational complexities with running the model at scale. The requirement for sampling also introduces the need to apply statistical weights to make national estimates from model results. The final, weighted sample then includes the salient parcel attributes that enable analysis in future steps—for example, the parcel location provides information on local grid conditions and resource availability, whereas the land-use type informs the available applications (behind or front of the meter) for analysis.

After the final, weighted sample is created, the second step involves sizing systems given the spatial attributes of the parcels. Both the outer boundary of the parcel and the location and footprint of any buildings are known and considered in the system sizing process. The model considers various siting constraints at this step as well, including the terrain slope and setback factors (for wind systems only). With this information, the system is sized to its maximum technical capacity, though for behind-the-meter parcels, system size is constrained by the annual on-site electricity consumption and/or the user-defined upper limit that restricts the total system size by technology.

The third step involves assessing the resource potential for each parcel. This step is enabled by NREL's reV tool, which takes information on local resource quality along with the technical configuration determined in the previous step and produces an hourly generation profile for both wind and solar technologies. This step relies on technology-specific performance characteristics (e.g., turbine power curve, solar PV module efficiency) that inform the annual and hourly generation outputs from reV. Appendix B provides details on these assumptions and characteristics.

[7] NREL's forthcoming ATB 2022 will, for the first time, include cost and performance projections for single-turbine distributed wind systems, most applicable to behind-the-meter applications.

Next, the valuation framework is applied to each parcel to conduct the economic analysis. The mechanisms behind this framework differ depending on the application (behind or front of the meter) but ultimately serve to introduce the costs and revenues specific to each system. For behind-the-meter systems, retail tariffs from the Utility Rate Database (OpenEI 2020) inform the amount of retail electricity costs offset by on-site generation; for front-of-the-meter systems, we used information on marginal grid conditions from Cambium (Gagnon et al. 2020) to estimate hourly revenues available at each parcel's location. Other variables, such as O&M costs, are also ingested and applied to each system at this stage.

With the valuation framework defined for each parcel, the fifth step involves calculating various economic and financial metrics that inform the viability of each system. This includes typical metrics such as net present value, payback period, and internal rate of return as well as the threshold CapEx, which estimates the CapEx required for the system to be profitable as defined by achieving a net present value of zero. See Section 2.4 for a complete description of this novel metric.

Finally, we collect and synthesize the outputs for each parcel in a postprocessing step. The multivariate nature of these model runs means that outputs are categorized by application (behind and front of the meter), technology (wind and solar), and scenario (see Section 3). The various cuts of these output data can help evaluate statistical distributions, analyze spatial trends, construct supply curves, and compare results.

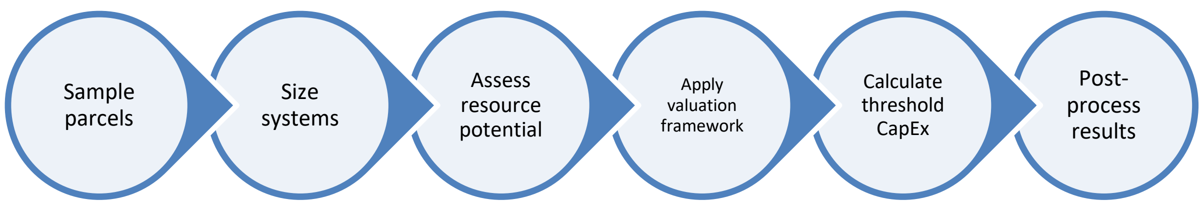


Figure 3. Model workflow to assess the threshold CapEx for all applications of distributed wind and solar

To illustrate the spatial layers and boundaries that comprise the parcel data set and demonstrate the detailed geospatial resolution that informs several steps in the model workflow described earlier, Figures 4 and 5 provide examples of parcels that represent a behind-the-meter and front-of-the-meter parcel, respectively.

Figure 4 shows an example of a parcel with an assigned land-use type of "single-family residence." For this example, we consider the siting and sizing of a behind-the-meter wind system (a behind-the-meter solar system would utilize the available roof area). The portion of the image that is a red boundary shaded in light blue represents the full extent of the parcel area, whereas the interior red boundary represents the building footprint of the residence attached to the parcel. The remaining area is the land that is available for siting a wind turbine. The geospatial methods developed for this study are applied at this stage and help identify the largest circle in the remaining land area (denoted in Figure 4 by the red circle)—this is the area within which a wind turbine could be sited. The final step in this process involves applying the setback factor, which results in the white circle in Figure 4—the final, optimal location for siting a wind turbine. In this example, the residential setting yields limited area available for siting a wind turbine. Thus, the maximum turbine size for this location (before consideration of the on-site electricity consumption) would be 2.5 kW—the smallest size represented in the model.

Figure 4. Satellite image of an example behind-the-meter parcel and its associated geographical boundaries located in northern California. ***Image from Google (2021)***

Figure 5 shows an example of a parcel with an assigned land-use type of "rural residence agricultural." For this example, we consider the siting and sizing of a front-of-the-meter wind system (a front-of-the-meter solar system would also utilize the available land area for siting ground-mounted solar). As with the behind-the-meter example shown in Figure 4, the various boundaries are highlighted in Figure 5—the light blue shaded region is much larger in this example, exemplifying the difference in application between a behind-the-meter and front-of-the-meter system. This example also has several on-site buildings, denoted again by the interior red boundaries. The geospatial methods are also applied at this stage, which result in identifying the largest circle in the remaining land area. In this case, the largest circle (in red) and the available area for siting after application of the setback factor (white circle) are more easily distinguishable because of the larger sizes involved with this parcel. As in the behind-the-meter case, the final, optimal location for siting a wind turbine (white circle) is the final output of this stage of analysis. For this front-of-the-meter example, the rural locale and greater available area allows for larger turbines to be sited on the property. The maximum wind turbine size for this location is 1.5 MW—the largest size represented in the model.

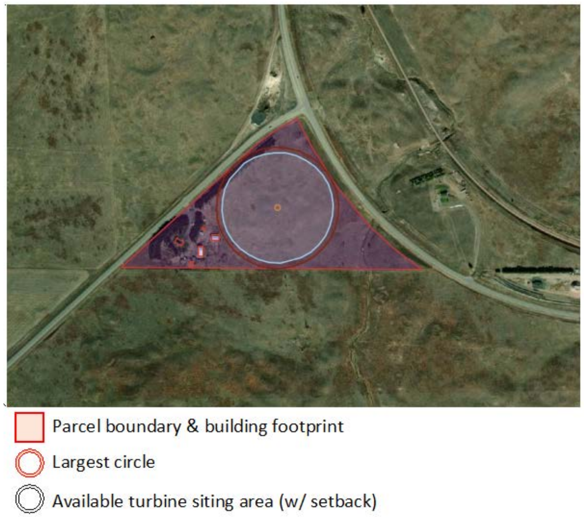


Figure 5. Satellite image of an example front-of-the-meter parcel and its associated geographical boundaries located in northwestern Nebraska. ***Image from Google (2015)***

While the exact locations of the parcels in these examples are withheld for privacy reasons, the parcel data set provides numerous locational attributes that allow us to attach several external data sets as well as apply the valuation framework and calculate the economic and financial metrics. For example, because the location of the behind-the-meter parcel (Figure 4) is known, we can determine the local resource attributes and the electric utility that serves that region; and because the land-use type of the parcel is known, we can infer the tariff that would be attached to the customer. Similarly, for the front-of-the-meter parcel (Figure 5), the known location provides the local resource conditions in addition to the Cambium revenues available to a system that is sited in that location.

In combination, these data provide a detailed, granular, parcel-level perspective on both the cost and value of distributed wind and renewable energy systems in these locations. This enables a highly resolved assessment of economic viability for each sampled parcel. Notably, these examples comprise just two parcels of the more than 150 million that are available in the full data set, demonstrating the power of the data set as well as the extensive modeling capabilities exhibited in this study. When aggregated by county, state, or region, we can better assess and report the technical and economic potential of parcels.

2.4 Threshold CapEx

An additional significant distinction from the 2016 report is the threshold CapEx framework used in this study. The threshold CapEx is intended to make it easy for developers and other stakeholders to determine the opportunity for a given location with a specific manufacturer or project CapEx. The threshold CapEx is a preferable metric relative to net present value because it is agnostic of technology capital cost. This perspective is important in an industry sector such as distributed wind energy when there are generally too few empirical data points with too much spread to compute a meaningful average or median value to accurately represent current costs. Moreover, the CapEx of a distributed system varies based on system size, location, and other factors. With relatively fewer kilowatts to normalize across these site-specific costs, parcel considerations can drive significant differences in system costs that are not easily accounted for or controlled with limited empirical data. Instead, developers can look at the threshold CapEx of a particular parcel to determine whether they could install a system for less than that amount and accordingly, generate renewable electricity at a rate that is both economical for the customer and profitable for the developer.

The threshold CapEx is defined as the dollars per kilowatt at which a system becomes viable given a site's resource potential, the technical performance of the system, the value of distributed generation, and the assumed operating life of the system. In other words, it represents the CapEx required for the project to be profitable, given a specific location, technology, and application behind or front of the meter. All other cost elements including O&M costs and financing are treated as inputs to the calculation and based on the best-available data. All systems having a CapEx equal to or lower than the threshold CapEx would have met or exceeded the required return on investment over the assumed operating life. Figure 6 provides an example of how the threshold CapEx supply curve can be used to determine the total capacity that would be economically viable for a given benchmark CapEx. In this example, a benchmark CapEx of $4,000/kW corresponds to an economic potential of approximately 750 GW; the total capacity of all evaluated sites or the technical potential is approximately 2,000 GW.

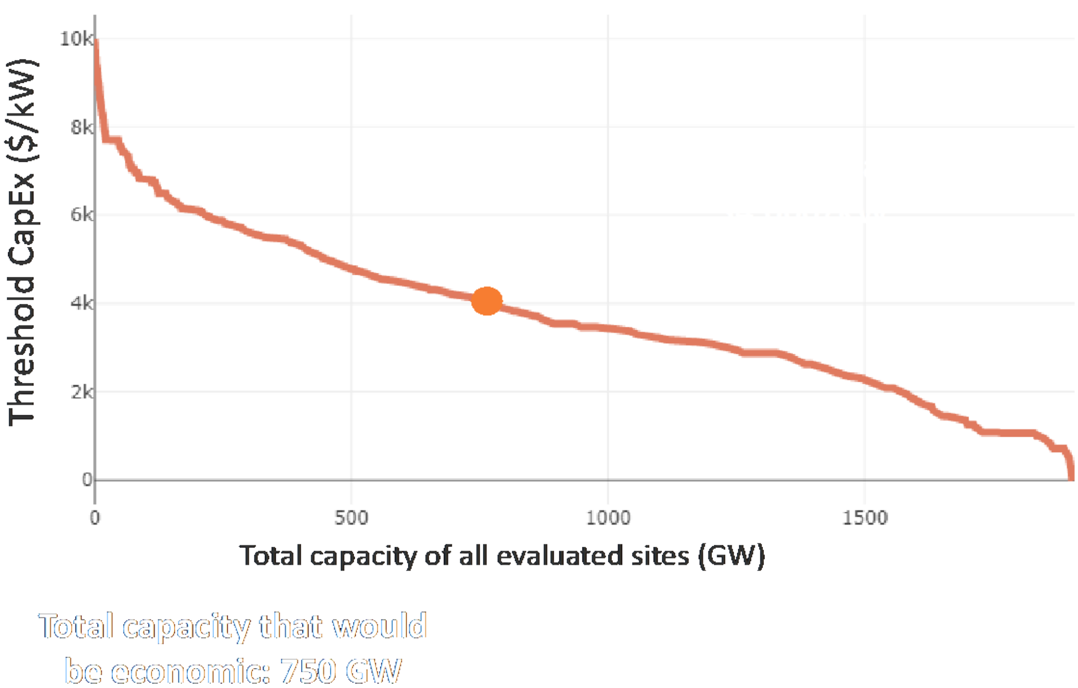


Figure 6. Example of how a specific project CapEx can be used to determine the total economically viable capacity or economic potential

Locations with higher threshold CapEx values are generally more suitable for DERs because they suggest a relatively high value-to-cost ratio for a given location. It is important to note, however, that the threshold CapEx is only a measure of the CapEx at which a project becomes profitable for a given location with a specific required internal rate of return; it does not mean that it is the best DER for a given location. The best DER for given location depends on the other available options for a particular site and their relative profitability. Threshold CapEx also assumes the system operates as expected—effectively with perfect foresight and zero risk. Importantly, the metric does not account for consumer adoption considerations or principles and therefore should not be confused with or portrayed as market potential. We expect that converting economic potential calculated from the threshold CapEx and plausible benchmarks into market potential would require increased standardization, lower consumer and performance risk, and workable regulatory and interconnection conditions, among other factors.

2.5 Analysis Limitations

Like any simulated exploration about the future, this work has some limitations. Regarding the underlying input data, several factors limit the geographic or spatial resolution. For example, hourly load profiles for each parcel are drawn from a set of reference load profiles generated by DOE for 16 commercial building types and residential buildings in different locations throughout the United States.[8] While this provides a realistic estimate of parcel load, historical data would result in a more accurate representation of each parcel's distributed wind behind-the-meter economic potential. Additionally, the load profiles we use rely on artificially smooth consumption patterns rather than real data, which is less regular (i.e., there could be certain hours that coincide to create very large spikes in demand). Further, the results are sensitive to scaling of load (by volume) for behind-the-meter systems, which affects bill savings directly. Ultimately, more site-specific representations of the load for an individual parcel could change the behind-the-meter results.

Another key limitation is tied to our reliance on future modeled estimates of the locational value of electricity to inform economic potential estimates for front-of-the-meter systems. Given the uncertainty that belies these analyses, resolving their insights across space and time is also difficult. In this study, revenues for front-of-the-meter systems are calculated with data from the Regional Energy Deployment System (ReEDS) model, which is resolved by balancing area and output for every other year.[9] As for behind-the-meter systems, the valuation of generation imore than local consumption depends on retail tariff data from the Utility Rate Database, which only includes rates for a subset of utilities in the United States.

As in 2016, the current work also suffers from limited distributed wind sector-specific data and an inability to consider cross-sector dynamic responses to model results. Our current approach (focusing on the threshold CapEx value as opposed to market potential) reduces the impacts resulting from limited sector-specific data but results in some trade-offs in terms of informing precise outcomes. Namely, we consider economic potential rather than consumer adoption; accordingly, we also do not consider social acceptance or related behavioral constraints on development that might impact how consumers value the relative economics offered by distributed wind energy. In addition, we cannot resolve the potential for social trends or phenomena that might make distributed wind systems particularly unfavorable or favorable. In

[8] See https://data.openei.org/submissions/153.
[9] See https://www.nrel.gov/analysis/reeds/about-reeds.html and https://www.nrel.gov/analysis/cambium.html.

other words, we do not capture significant socially driven negative or positive dynamic feedback loops within the scenarios studied.

Finally, as in the Lantz et al. (2016) analysis of distributed wind, the 2022 study potential was conducted through the lens of NREL's dWind model (Sigrin et al. 2016). As discussed in Section 2.1, the dWind model evaluates the resource, economics, siting, load, and policy conditions for millions of potential distributed wind energy sites across the nation. As a national-scale deployment model, dWind lacks the precision to inform individual investment decisions and relies on generalized patterns of consumer behavior that likely vary widely across the study area. Given these data and modeling limitations, we conducted a rigorous peer-review process and enlisted a technical review committee to provide additional expert input for consideration in the development and execution of our work. In addition, we used existing historical data (where available) to calibrate model outputs.

With these and other assumptions and simplifications in mind, the results detailed throughout the report are useful for understanding trends in potential as well as key variables and sensitivities. However, they should not be interpreted as predictions of future behind-the-meter distributed wind energy deployment or DOE or NREL targets.

2.6 Future Opportunities for Analysis and Model Advancements

Capability advancement and future analyses are of interest in multiple domains. These efforts could provide increasingly resolved and relevant market insights across the contiguous United States. Further, they can inform new market segments and commercial opportunities. For example, integration of battery storage into dWind would provide a quantitative understanding of opportunities for distributed hybrid systems and show land-use types, regions, and disadvantaged communities where storage adds the most value. Notably, battery storage as a complement to wind and solar PV, or as a standalone asset, is already enabled by the PySAM integration. Future work would be geared toward streamlining software to enable rapid processing and problem solving. Integrating storage adds complexity to hybrid system dispatch and greatly increases the number of mathematical dimensions that need to be computed.

Another improvement would be enhanced wholesale electricity price characterizations. This gap primarily impacts the front-of-the-meter results derived from Cambium, which models an optimized power system and outputs marginal metrics. The optimized nature of these outputs means that the revenues available to front-of-the-meter applications are decoupled from empirical prices and tend to undervalue the energy that a front-of-the-meter application would produce in the real world. We primarily rely on Cambium because it is the only known data set that has the required scale for our simulation needs: comprehensive of the entire contiguous United States, forward-looking (through 2050), and scenario-based. However, an improved analysis of the front-of-the-meter market would require using more empirical data for the locations being studied. A detailed, location-specific case study approach would help gather electricity market data that is more accurate and applicable to the parcels in that area, allowing us to better understand the potential error or bias in the use of Cambium data across larger regions. This work could also explore different valuation schemes for community-owned wind as a subset of front-of-the-meter applications, with possibilities such as virtual net metering or similar aggregated consumer mechanisms that support the financing and assign appropriate valuation schemes for community-based energy development. This latter work could be of particular interest in disadvantaged communities.

A complement to improved wholesale price data would be more site-specific parcel load profiles to inform the behind-the-meter system value. In our current approach, the model attributes each parcel with a normalized hourly electric consumption pattern that is scaled to meet the annual consumption of the agent (as in Sigrin et al. [2016]). These hourly consumption data are based on building models for 16 building types (15 nonresidential, 1 residential). This contrasts with the 200-plus distinct land-use types that are included in the parcel data set—thus, mapping of load profiles is a one-to-many situation that does not consider “microtrends” in consumption that may be region-specific, land-use-specific, and so on. As no other data sets with the necessary scale are known to improve this limitation, a detailed case study in this instance could help collect granular consumption and hourly profile data to better assess the representativeness of the current approach. Enhancing the load profiles might also more explicitly consider the potential for increased electrification of the transport and home heating sectors, which might profoundly impact consumers’ electricity consumption.

Another challenging but useful area for future work is creating a geospatial method to analyze combined adjacent parcels. Presently, real-world ownership issues are explicitly ignored in our current approach—the ability to site and size wind turbines is strictly considered within the boundaries of a single parcel only. However, developing methods that better account for obstructions in adjacent parcels or potentially the ability to site a turbine based on the area of multiple parcels would enable better simulation of the type of real-world opportunities and challenges that exist in working with neighbors to site and install wind turbines.

Other specific opportunities for further analysis and model application include:

- Conducting deeper analysis of trade-offs and opportunities in disadvantaged communities
- Studying and comparing the impacts of different retail tariff structures, financial incentives, and other policies that impact the threshold CapEx of distributed energy resources
- Digging further into parcel-level data and results to identify sites worthy of more detailed resource assessment and potentially project development
- Pursuing new research focused on consumer adoption to better understand current and future consumer uptake barriers to distributed wind energy.

3 Scenario Framework

There are eight scenarios that are investigated in this study. Each scenario analyzes the sensitivities to single or multiple input parameters. The five main categories of inputs for which we analyze sensitivities are cost and performance (for large wind turbines only), financing, policy extension including for the Investment Tax Credit (ITC), market value or compensation levels for DERs, and ease of siting. We include one optimistic scenario that assumes movement in support of distributed wind across multiple fronts by combining the most favorable assumptions from each of the other sensitivities that we model. Table 1 provides a summary of all modeled scenarios. A short description of each scenario and its core inputs, with additional specifics in Table 1, is included here.

Notably, these scenarios reflect snapshots in time based on the specified conditions. This approach contrasts with similar comparable work including Lantz et al. (2016), whereby a given scenario produced results through time. For this study, we selected the years 2022 and 2035 as our two snapshots in time. We employed this approach to effectively manage high-performance computational resources given the number of sites sampled (1 million each for behind-the-meter and front-of-the-meter conditions) and needing to be processed and manage the results data and their dissemination. Notwithstanding our approach, our two baseline scenarios could be thought of as two slices from a common set of business-as-usual conditions that vary through time.

3.1 Baseline 2022 Scenario

The Baseline 2022 scenario relies on cost (for costs other than CapEx) and performance projections from NREL's 2020 ATB Moderate Scenario.[10] NREL's ATB is an annual effort designed to provide cost and performance assumptions for an array of electricity generation technologies including wind energy systems. The ATB is used by electricity system modelers exploring potential changes in the mix of generation and capacity for a given region through time. The moderate scenario reflects a median or expected scenario for cost and performance trends; however, as this scenario is grounded in the year 2022, its divergence from other possibilities is relatively limited. In addition, for the Baseline 2022 scenario, we assume policies as currently legislated to inform our valuation of behind-the-meter systems. Front-of-the-meter revenues are determined using NREL's Cambium Midcase scenario for the year 2022.[11] Small wind systems are assumed to be eligible for the small wind ITC. Front-of-the-meter systems are assumed to be eligible for the wind energy Production Tax Credit (PTC) at 60%, given our premise that they are businesses selling to a third party of some form (e.g., a corporation or utility).[12] Baseline assumptions for siting assume a 1.1x setback from property boundaries and structures. Financing assumptions for this scenario include return on equity rates of 6.1%, debt interest rates of 1.46%, and down payment fractions (i.e., equity shares) of 46%.

[10] See https://www.nrel.gov/analysis/standard-scenarios.html.

[11] Cambium—the model's source of hourly cost, emissions, and operation data for the U.S. electric sector—can also be run for NREL's Standard Scenarios that model high vehicle electrification or drastic reductions in the cost of renewable energy. See https://www.nrel.gov/analysis/cambium.html.

[12] For this scenario, front-of-the-meter systems were only given the option for the PTC; however, given relatively high capital costs and potentially lower capacity factors, an ITC might ultimately be more attractive for these projects. For this reason, our scenario provides the ITC to both behind- and front-of-the-meter systems; it does not include a PTC option.

3.2 Baseline 2035 Scenario

Building from the Baseline 2022 scenario, the Baseline 2035 scenario is best characterized as the "business-as-usual" case computed for conditions in 2035. This scenario also depends on the NREL ATB Moderate case cost and performance assumptions albeit for 2035 and considers expected policy changes in behind-the-meter valuation including switching from net metering to net billing. Front-of-the-meter revenues are determined using NREL's Cambium Midcase scenario for the year 2035. Both the small wind ITC and the PTC are assumed to be expired. Financing assumptions for this scenario include return on equity rates of 6.1%, debt interest rates of 2.4%, and down payment fractions (i.e., equity shares) of 33%. Debt rate assumptions are increased slightly in this scenario based on a gradual trend toward more historical benchmark lending rate conditions. For simplicity and because equity rates are less coupled to these benchmark lending rates, equity return assumptions are constant between the 2022 and 2035 baseline conditions. Assumptions for siting are consistent with the Baseline 2022 scenario.

3.3 Cost and Performance Scenario

This scenario varies the applicable cost and performance assumptions, for costs other than CapEx, and for large wind turbines only. All other input parameters remain the same as the Baseline 2035 scenario. Specifically, the Cost and Performance scenario relies on the advanced cost and performance projections from NREL's 2020 ATB for larger turbines. Under these conditions, large wind turbine performance is improved, and operation and maintenance costs are lower. In principle, these changes in cost and performance would increase the threshold CapEx for a given location because energy generation would improve, and additional revenue could be captured. In practice, this scenario has limited impacts on our results because its implementation is narrowly applied to large wind turbines.

3.4 Financing Scenario

This scenario relies on the advanced projections for financing parameters from NREL's 2020 ATB. Specifically, as a sensitivity on the Baseline 2035 scenario it holds the return on equity at 6.1% and the debt interest rates at 2.4% but pushes the down payment fractions down to 20%. This reduction in the down payment fraction allows the project to reduce the share of relatively higher cost equity in the project, meaning more of the initial investment capital is provided by low-cost debt and delivers a lower weighted average cost of capital. As a sensitivity supporting a lower overall weighted average cost of capital, this scenario lowers the threshold internal rate of return needed to reach a net present value of zero and subsequently increases the threshold CapEx for sites. All other input parameters remain the same as the Baseline 2035 scenario.

3.5 Investment Tax Credit Scenario

This scenario assumes a tax credit of 30% for both distributed solar and wind. All other input parameters remain the same as the Baseline 2035 scenario.

3.6 Value of Distributed Energy Resource Scenarios

There are two Value of DER sensitivities—the High DER Valuation sensitivity and the Low DER Valuation sensitivity—which reflect the compensation received for energy produced by distributed wind and solar. The naming convention reflects the Cambium data that are used in each scenario for front-of-the-meter valuation—the High DER Valuation scenario uses the High

Renewable Energy Cost Scenario (Cole), whereas the Low DER Valuation scenario uses the Low Renewable Energy Cost Scenario (Cole). All else being equal, higher renewable energy costs in the core Cambium scenario increase the cost of electricity generation, generally resulting in higher values for marginal generation, including from DERs. This increase is in contrast with low renewable energy costs, which result in lower cost of electricity generation and generally lower values for marginal generation, including from DERs. The distinction between these scenarios is intended to capture nuances in the revenues available to front-of-the-meter systems. The High DER Valuation scenario provides a larger average revenue available over a given year relative to the Baseline 2035 scenario. The Low DER Valuation scenario provides a larger maximum revenue relative to the Baseline 2035 scenario, meaning a front-of-the-meter system could capture a much higher revenue for generating in a specific hour. For behind-the-meter systems, both scenarios assume an extension of the present-day (2022) net-metering policies. All other input parameters remain the same as the Baseline 2035 scenario.

3.7 Siting Scenario

In the baseline scenarios, the setback factor for distributed wind is 1.1 times the wind turbine tip height. The Siting scenario tests the sensitivity to relaxed siting by reducing the setback factor for wind to 0.55 times the turbine tip height. All other input parameters remain the same as the Baseline 2035 scenario.

3.8 Optimistic Scenario

This scenario combines the Financing, Cost and Performance, ITC, High DER Valuation, and Siting scenarios and reflects the best conditions for distributed wind and solar that we model.

Table 1. Scenarios To Examine How Evolution in Cost, Performance Valuation, and Policy Impact the Potential of Distributed Wind and Solar Energy

Number	Scenario Name	Sensitivity Parameters	Rationale
1	Baseline 2022	2022 baseline costs and policies	Identify current (2022) economic potential with baseline assumptions
2	Baseline 2035	2035 baseline cost projections; projected policies for DER value	Identify future (2035) economic potential with baseline assumptions
3	Cost and Performance	Improvements in cost and performance for large turbines only	Impact of optimistic costs and performance, but in this model setup the changes are only applicable for large turbines
4	Financing	Improved financing conditions	Impact of financing
5	ITC	ITC at 30% for both wind and solar	Impact of ITC
6	Value of DERs	A. Higher value of DERs B. Lower value of DERs	Impact of compensation mechanisms and wholesale market prices
7	Siting	Decreased setback factor	Impact of relaxed siting considerations
8	Optimistic	2035 advanced cost projections, higher DER value, improved financing conditions, ITC, siting	Impact of optimistic costs + high DER value + financing + ITC + relaxed siting

4 Results

In this section, we present the results of our analysis across multiple dimensions. We include a focus on the current conditions faced by the industry using data from the Baseline 2022 scenario. In addition, we analyze the 2035 results across the array of sensitivities. Within our assessments, we use the threshold CapEx metric and include detail on the technical and economic potential for distributed wind energy under the scenarios studied. Highlights from the solar PV results are included in Appendix E. We also seek to identify regions and sectors where opportunities for distributed wind energy exist. We conclude our results with an analysis of the potential for distributed wind in disadvantaged communities. The potential for distributed wind to impact electricity grid decarbonization is discussed in Section 5.

4.1 Technical Potential

The threshold CapEx for each parcel ranked from highest to lowest produces a supply curve that identifies the total available distributed wind capacity in behind-the-meter and front-of-the-meter applications under the different scenarios. Figure 6 in Section 2 provides an example of how technical potential is determined using the threshold CapEx supply curve. The total capacity under the threshold CapEx supply curve for the Baseline 2022, Baseline 2035, and Optimistic scenarios are presented as the technical potential in Table 2.

We calculated the technical potential quantities for wind using the developable land area for each sampled parcel and applying an energy density factor of 3 MW/square kilometer (km^2) (Lopez et al. 2021).[13] The technical potential reported using the fixed energy density factors does not consider the theoretically higher capacity density that is possible when reducing the minimum setback requirements, as is applicable in the Siting and Optimistic scenarios. It does, however, account for an additional parcel (area) that is now able to site a wind turbine under the more relaxed siting criteria specific to the Siting and Optimistic scenarios. Therefore, the technical potential for these scenarios is higher than the technical potential for the baseline scenarios. In addition, parcels with extremely high threshold CapEx values (higher than the 99^{th} percentile) as well as threshold CapEx values at or very near 0 (lower than the 1^{st} percentile), both considered outliers, are excluded from the threshold CapEx supply curves. As the economic conditions for distributed wind in these scenarios vary, this dynamic could result in somewhat higher technical potentials for scenarios that have more favorable economics for distributed wind energy.

Technical potentials for 2022 and 2035 as well as the upper-bound Optimistic scenario are covered in Table 2. Values estimated are terawatt (TW) scale for both applications. Front-of-the-meter potentials are on the order of 4 TW and 5 TW under baseline conditions and 6 TW in the Optimistic scenario. Behind-the-meter technical potential is on the order of 2 TW in all scenarios. Front-of-the-meter systems observe the largest increase in technical potential as a result of the relaxed siting constraints, which are present in Table 2 in the Optimistic scenario. This increased technical potential for front-of-the-meter systems occurs because more sites become possible for front-of-the-meter applications given that they are unconstrained by local load or consumers. Because behind-the-meter systems are constrained by local load, not just

[13] For regions with many small, behind-the-meter wind turbines, our approach likely overstates the real-world potential for these locations because for small wind applications, the 3-MW/km^2 density value likely exceeds what can possibly be achieved in practice.

siting considerations, and we apply the generic energy density calculation for all sites that are eligible for a behind-the-meter wind turbine to compute technical potential, the impacts of relaxed siting on technical potential for behind-the-meter applications are relatively muted. In practice, the impacts of relaxed siting for these systems could reasonably be expected to be larger, particularly for some locations.

Table 2. Technical Potential for Behind-the-Meter and Front-of-the-Meter Applications for Distributed Wind Energy[14]

Application	Technology	Technical Potential (GW)		
		Baseline 2022	Baseline 2035	Optimistic
Front of the Meter	Wind	5,380	4,102	6,149
Behind the Meter	Wind	1,747	1,749	1,846

4.2 Economic Potential

The economic potential for each scenario is determined by the threshold CapEx supply curves for the respective scenarios and an "economic" benchmark. Figure 6 in Section 2 provides an example of how technical and economic potential are determined, using the threshold CapEx supply curve and a benchmark CapEx value.

4.2.1 Benchmark CapEx Values Informing Economic Potential

For the Baseline 2022 scenario, the economic potential for behind-the-meter applications is calculated using a CapEx benchmark of $5,675/kW (Stehly, Beiter, and Duffy 2020). For the Baseline 2035 scenario and all 2035 sensitivities, the economic potential for behind-the-meter applications is calculated using a CapEx benchmark of $4,354/kW. These benchmarks are grounded in or projected from estimated current market costs and intended to reflect economically viable project cost levels. They are therefore indicative of economic potential. Although behind-the-meter applications can include all wind turbine sizes, sectors, and land-use types, these benchmark CapEx values are informed by 20-kW cost characterizations. This approach is admittedly conservative (i.e., understates the potential) for larger systems that often have lower dollar-per-kilowatt values based on economies of turbine size; however, we use these single benchmark values for simplicity and ease of replicability. In addition, in this instance, because the individual supply curve points are not sorted by system type, using a CapEx benchmark that is more in line with larger commercial or industrial behind-the-meter applications might overstate economic potential by adding sites in which large wind turbine installations are not feasible.

For the Baseline 2022 results, the economic potential for front-of-the-meter applications is calculated using a benchmark CapEx of $1,608/kW. This benchmark is based on estimated costs

[14] The technical potential is calculated using the developable land area for each sampled parcel and applying energy density factors (energy density for wind is assumed to be 3 MW/km^2 (Lopez et al. 2021) and energy density of solar is assumed to be 0.022 kW/square foot) to determine the technical potential. Front-of-the-meter solar energy considers ground-mounted solar while behind-the-meter solar considers rooftop solar technical potential.

for a 2.8-MW turbine located at a large utility-scale wind project (Stehly, Beiter, and Duffy 2022). On top of the CapEx from Stehly, Beiter, and Duffy (2020), we add a 10% cost premium to account for the expected smaller size of front-of-the-meter projects (e.g., 5 to 20 MW) as compared to the approximately 100-MW utility-scale projects that provide the foundational empirical data for this value. This premium is included, as front-of-the-meter systems are not expected to have access to economies of plant size that are in effect for larger facilities. The 10% cost adder is also derived from empirical market data of project CapEx by project size reported by Wiser and Bolinger (2021). For the Baseline 2035 scenario and all 2035 sensitivities, the economic potential for front-of-the-meter applications is calculated using a benchmark CapEx of $993/kW. This value is derived from the 2021 NREL ATB Moderate land-based wind CapEx trajectory for utility-scale plants and the respective reference (Class 4) value for the year 2035. It also includes an additional cost premium of 10% on top of the original ATB value; again, to account for the smaller plant size expected for front-of-the-meter distributed applications.

Although front-of-the-meter applications include multiple wind turbine sizes greater than 100 kW as well as multiple sectors and land-use types, these single-benchmark CapEx values for each snapshot in time are used here for simplicity and replicability. Moreover, because front-of-the-meter systems are not constrained by consumer load, the model selects as large a turbine as can be sized on a given parcel and larger turbines in general, reducing the potential error resulting from a single benchmark value derived from larger wind turbine installations.

Notwithstanding the caveats noted earlier, the values reported by Stehly, Beiter, and Duffy (2020) and the NREL ATB were selected because they are well-documented and readily accessible estimates of land-based wind energy capital costs. There is no equivalent publicly available value specifically for front-of-the-meter distributed-scale projects. Further, the projections detailed in Appendix B are targeted toward single-turbine projects that Wiser and Bolinger (2021) show tend to incur a significantly larger cost penalty than hypothetical 20-MW facilities that we believe are generally consistent with market expectations for future front-of-the-meter applications.

4.2.2 Aggregate Economic Potential Results

Behind-the-meter wind systems in the Baseline 2022 scenario have approximately 919 GW of economic potential. For the Baseline 2035 scenario, which represents cost and policy conditions in 2035, economic potential is 773 GW for behind-the-meter wind. Front-of-the-meter wind under the Baseline 2022 scenario has approximately 474 GW of economic potential. In comparison, for the Baseline 2035 scenario, front-of-the-meter economic potential is 160 GW.

Economic potential under the baseline scenarios is higher in 2022 than in 2035 as a result of the expected sunset of both the small wind ITC, which provides a 26% investment tax credit to systems that are 100 kW or less for systems installed prior to January 1, 2023, and the wind energy PTC, which provides a $0.015/kilowatt-hour production tax credit to systems selling to a third party and that commenced construction in 2020 and 2021. In many cases, by 2035 net-metering policies for behind-the-meter systems will sunset or transition.

In addition, these results show generally higher economic potential for behind-the-meter systems, relative to front-of-the-meter systems, under baseline conditions. As shown in Section 4.3, this finding holds true in all our scenarios except the two scenarios with a 30% ITC available to all distributed wind energy technologies. This result is likely due to the relatively higher value that behind-the-meter systems can extract by offsetting retail electricity consumption as compared to front-of the-meter systems that are valued at wholesale electricity rates. In addition, in practice, front-of-the-meter applications might offer additional value not captured in the economic assessments performed here; for example, if they are set up as community wind projects, if they can monetize their renewable energy credits, or if they can defer other potential upgrades or investments in the distribution network or add reliability and resilience. Monetizing these value streams would, all else being equal, increase the economic potential for front-of-the-meter systems.

These estimates show terawatt-scale economic potential for distributed wind energy applications both in 2022 and 2035. These quantities of economic potential demonstrate that the opportunity for the industry to contribute to the nation's energy future is meaningful and that identifying those locations that offer the best value-to-cost ratio, as indicated by high threshold CapEx estimates, is worthwhile. Subsequent results sections seek to illuminate those locations with the most parcels that meet our simple definition of economic potential as well as those with the highest threshold CapEx values. At the same time, when contrasting these results with recent market activity it is apparent that profitability alone is a necessary but not sufficient achievement to drive widespread deployment of distributed wind energy systems. Being able to compete with other DERs through lower costs and drive down life cycle and customer acquisition costs may also be important.

4.3 Aggregate Economic Potential Results by Scenario

Here, we present the economic potential for each scenario. The economic potential is determined by the threshold CapEx supply curves for the respective scenarios and benchmark CapEx values described in Section 4.2. Figure 7 shows the supply curves for the Optimistic, Siting, Baseline 2035, and Baseline 2022 scenarios in behind-the-meter applications. Only a subset of the full suite of scenarios is shown to allow for easier interpretation. Figure 8 shows the supply curves for the Optimistic, Siting, Baseline 2035, and Baseline 2022 scenarios for front-of-the-meter applications. Table 3 shows the economic potential for each scenario we studied using the respective benchmark values described in Section 4.2.

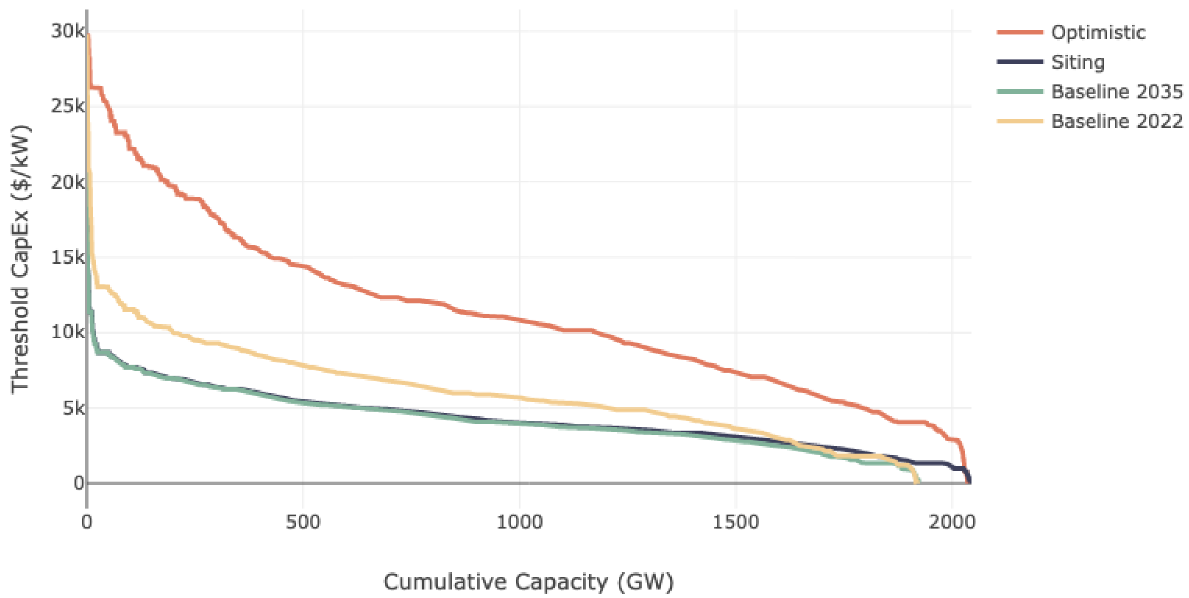


Figure 7. Supply curve for behind-the-meter distributed wind applications under the Optimistic, Siting, and Baseline scenarios

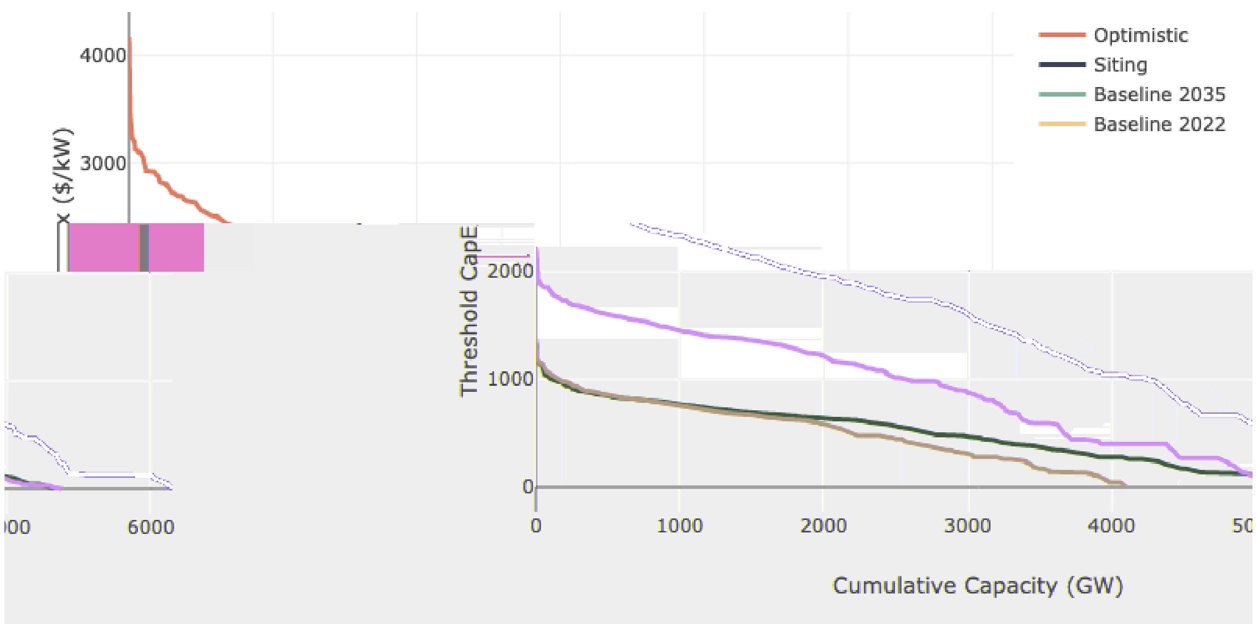


Figure 8. Supply curve for front-of-the-meter distributed wind applications under the Optimistic, Siting, and Baseline scenarios

Table 3. Economic Potential for All Scenarios[15,16]

Scenario	Economic Potential in 2022 (GW)		Economic Potential in 2035 (GW)	
	Behind the meter	Front of the meter	Behind the meter	Front of the meter
Baseline 2022	919	474		
Baseline 2035			773	160
Siting			803	115
Cost and Performance			773	342
DER Valuation			748	256
Financing			984	513
ITC			1,472	2,152
Optimistic			1,673	4,264

Note: Given relatively higher capital costs and potentially lower capacity factors, we assume the ITC is generally more favorable for distributed wind applications relative to utility-scale wind; accordingly, our ITC scenario focuses exclusively on the ITC.

From these data, there are a variety of noteworthy outcomes. First, although the Siting scenario increases the technical potential for both behind-the-meter and front-of-the-meter systems, the impact on threshold CapEx values, especially for the sites with the highest values, is not significant and therefore the impacts on economic potential are mixed. This outcome is intuitive, as the primary benefit of our Siting scenario is to allow wind turbines to be placed in more locations. In principle, simply allowing turbines in more locations would have no direct effect on project economics. In practice, greater ease of siting requirements might also be correlated with lower permitting and development costs, providing some degree of direct cost savings. This potential cost savings is not included in our Siting scenario design.

A second observation consistent with the discussion in Section 4.2.2 is simply that the threshold CapEx values for behind-the-meter systems appear to be substantially higher than for front-of-the-meter systems. This is certainly the case for the top 500 GW or so of potential for both applications and reflects the modeled difference in revenue potential for these two types of applications, as described in Section 4.2.

A third observation is that policy changes with a financial impact such as the 30% ITC can have a sizable effect on plant-level economics; this is reflected in the threshold CapEx values and reported economic potential values. In addition, the increased threshold CapEx values for front-of-the-meter systems that occurs with a 30% ITC indicates the overall potential of the technology

[15] The economic potential in 2022 is determined by considering the benchmark CapEx of $1,608/kW for front-of-the-meter wind applications and $5,675/kW for behind-the-meter wind applications. The economic potential in 2035 is determined by considering the projected benchmark CapEx of $993/kW for front-of-the-meter wind applications in 2035 and $4,354/kW for behind-the-meter wind applications in 2035.

[16] The economic potential also considers an energy density of 3 MW/km^2 for wind.

under the right economic conditions and demonstrates that if the requisite economic thresholds can be met, then the opportunities for these distributed systems can be substantial.

These outcomes informed from the supply curve and threshold CapEx data are consistent with the economic potential results in Table 3. Notably, the scenario that has the biggest impact on economic potential is the ITC scenario. The ITC increases the economic potential of front-of-the-meter applications by 1,992 GW and behind-the-meter applications by 699 GW, relative to the Baseline 2035 results. Financing parameters are the next biggest factor boosting economic potential, with an increase of 353 GW for front-of-the-meter applications and 211 GW for behind-the-meter applications. There does not appear to be a significant change in our results for the Cost and Performance scenario; however, our input parameter assumptions do not change for behind-the-meter applications. Therefore, the 182 GW increase in economic potential is observed only for front-of-the-meter applications because of changes in large turbine capacity factor and O&M cost reductions. In this instance, the limited observed effect is a function of scenario and analysis design rather than a true indication of the ability of cost and performance to alter system economics. Potential value, not shown in our results, from improved cost and performance is particularly evident when distributed wind is compared against competing DERs wherein lower cost and better performance may be a prerequisite for competitiveness even if profitability can be realized at current cost levels. Finally, both the DER valuation and siting scenarios increase economic potential, but by relatively modest amounts.

While relaxing siting conditions can increase technical potential, much of this capacity is not economic unless conditions of favorable policy and lower costs are also present. Improved siting alone tends to offer benefits only for relatively low threshold CapEx sites, and we do not see an increase in economic potential under this scenario for front-of-the-meter applications. The Optimistic scenario considers lower cost projections, an extension of net-metering policies, a 30% ITC, relaxed siting, and higher revenues from the wholesale market, and thus represents a theoretical upper bound of economic potential. Under this scenario, the economic potential increases by 900 GW for behind-the-meter applications and by 4,104 GW for front-of-the-meter applications.

The economic potential revealed by these aggregate national results suggests both large quantities of profitable distributed wind energy today and in the future as well as significant sensitivities to variable changes within the modeled scenarios. For 2022, as noted earlier, there are nearly 1.4 TW of economic potential estimated for distributed wind energy. Terawatt-scale potential is also shown in each of the 2035 scenarios and especially in the Financing, ITC, and Optimistic scenarios. However, economic potential is a necessary but not sufficient condition to drive widespread deployment of distributed wind energy systems. Competing with other DERs through lower costs and driving down life cycle and customer acquisition costs may also be important. Further, given competition between DERs, including wind and solar, close examination and analysis of proposed policy provisions and their applicability to distributed wind is important if stakeholders seek to convert distributed wind energy's potential into deployment. Overall, long-term economic potential is highly sensitive to future policies, especially those that impact project-level economics. If current tax credits and net-metering policies expire as scheduled, economic potential will drop between 2022 and 2035. However, if current tax credits and policies are extended and modestly expanded, economic potential increases by more than 80% for behind-the-meter applications and by a factor of nearly nine for front-of-the-meter applications.

4.4 Results by Region and Sector

Here, we present our analysis results specific to regions, land-use type, and sectors. Results are presented separately for front-of- and behind-the-meter applications. These results focus only on distributed wind. All maps rely on threshold CapEx metric to highlight the best locations in each region and state; tables detail the economic potential by state for the top states. As economic potential is based on threshold CapEx, mapped areas with high threshold CapEx values across broad regions are correlated with the economic potential tabular results. Given its relative market relevance, state and county-level data are drawn only from our Baseline 2022 scenario. Some national results show both 2022 and 2035 results. Under Baseline conditions, which are intended as reference conditions, these data should provide plausible insights regarding high-value locations to target for distributed wind energy development today and into the next decade.

4.4.1 Front-of-the-Meter Applications

Threshold CapEx is shown across the contiguous United States for front-of-the-meter applications under the Baseline 2022 scenario in Figure 9; Figure 10 details the same metric for the Baseline 2035 scenario. From these figures, we see that the Great Plains, Midwest, and South Central regions have generally higher threshold CapEx values in 2022 and 2035. These results illustrate that projects in locations where there is a higher-quality wind resource are more likely to be economically viable for front-of-the-meter applications. Although this fact seems intuitive, it is not strictly the case because systems with a modest wind resource and high-value electricity can also return high threshold CapEx values, as shown in portions of the East and interior West.

Although the spatial patterns of opportunity are similar between 2022 and 2035, there are some differences. Where those differences exist, they are a function of actual changes in policy (e.g., the sunsetting of the wind energy production tax credit) and changes in modeled wholesale power prices and hence the value of front-of-the-meter applications between the two snapshots in time. For stakeholders interested in near-term development or demonstration opportunities, focusing on those locations from the 2022 results in the Great Plains and Midwest would be a useful place to start, with further study of potential locational pricing and value to follow.

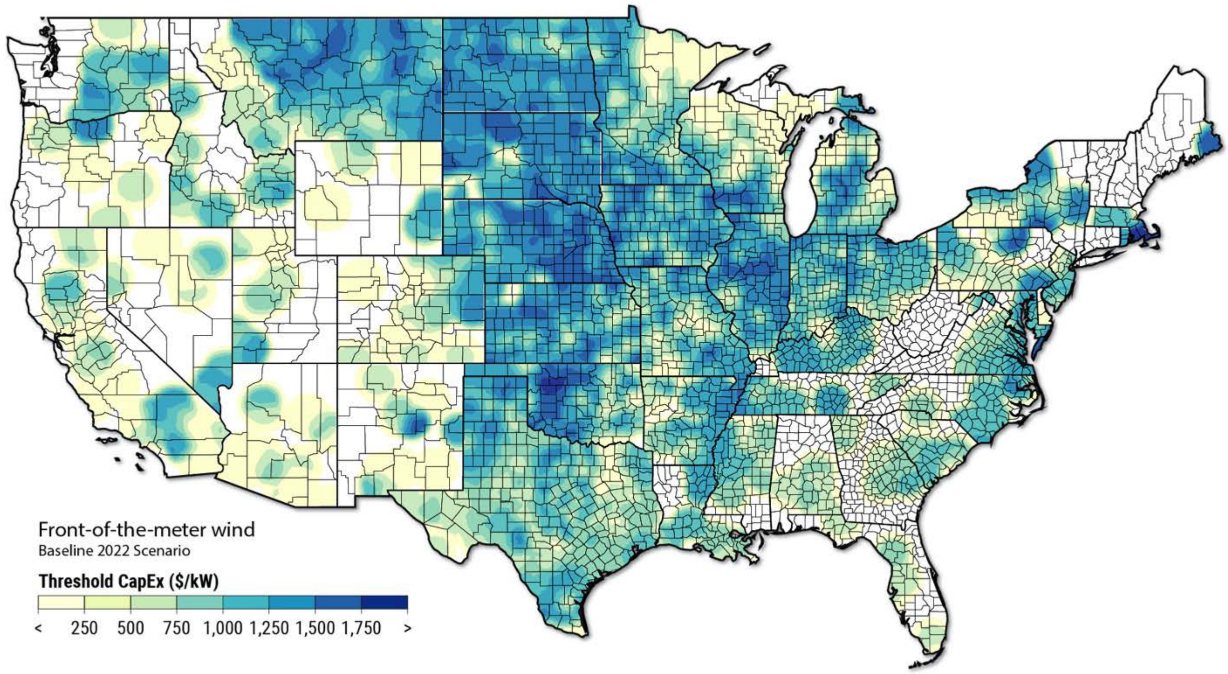


Figure 9. Front-of-the-meter wind threshold CapEx by state and county; Baseline 2022 scenario

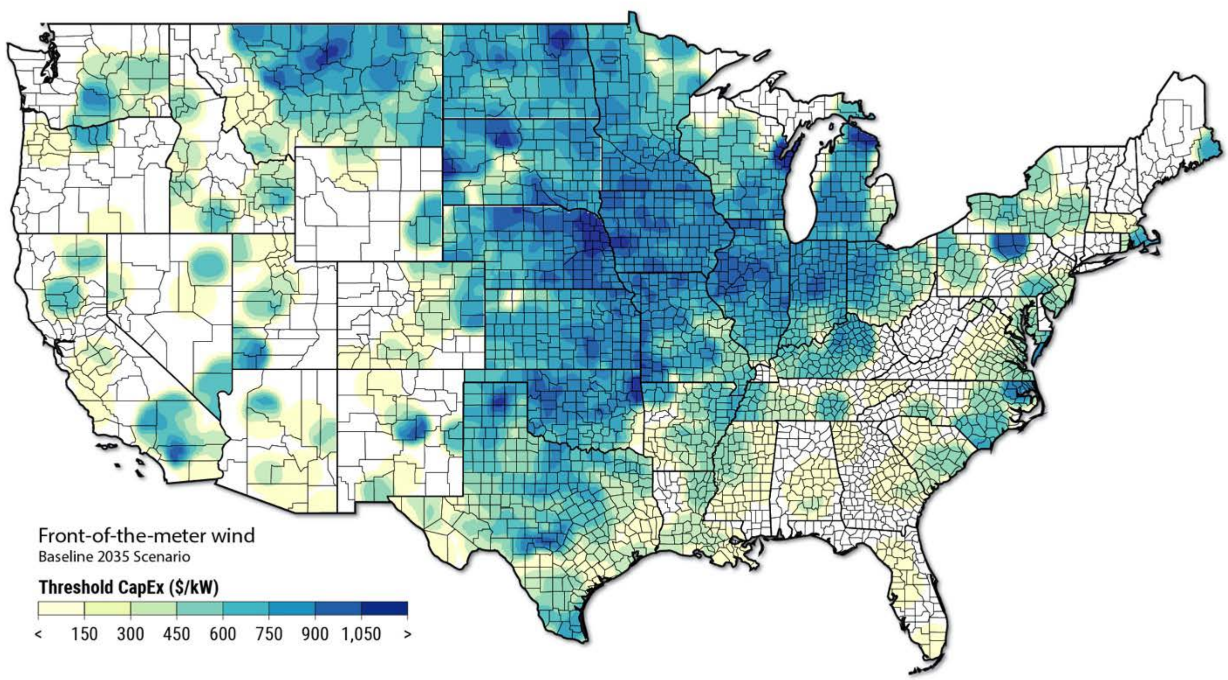


Figure 10. Front-of-the-meter wind threshold CapEx by state and county; Baseline 2035 scenario

Using the Baseline 2022 scenario, Table 4 presents the top 10 states in the contiguous United States ranked by economic potential. The 80th percentile threshold CapEx in the state is presented in the third column, followed by the technical potential in the fourth column. The 80th percentile threshold CapEx value reflects the minimum threshold CapEx value of the top 20% of parcels in each state. Stated differently, it is the value exceeded by the best 20% of parcels in each state. We use the 80th percentile because developers will be reasonably expected to concentrate their efforts on the most profitable locations and are therefore more interested in an 'above average' value as compared to an average or median value. Technical potential is included to help illuminate the overall share of the technical potential that is economic. Economic potential is calculated using the same 2035 benchmark CapEx value presented in Section 4.2, of $993/kW for front-of-the-meter distributed wind applications.

Oklahoma, Nebraska, Illinois, Kansas, Iowa, and South Dakota are the six states with the largest quantities of front-of-the-meter economic potential (Table 4). Although several have hundreds of gigawatts of technical potential, economic potential in these leading states is mostly on the order of tens of gigawatts. Figure 11 provides more granular information by highlighting the counties within the top six states that have the highest threshold CapEx values.

Table 4. States With the Largest Economic Potential for Front-of-the-Meter Applications (Baseline 2022 Scenario)

State	Economic Potential 2022 (GW)	80th Percentile Threshold CapEx ($/kW)	Technical Potential (GW)
Oklahoma	103.9	1,684	202.2
Nebraska	56.8	1,722	269.6
Illinois	56.7	1,595	410.3
Kansas	46.6	1,598	226.0
Iowa	32.7	1,663	134.5
South Dakota	28.5	1,580	137.0
Pennsylvania	28.3	1,223	79.2
New York	21.5	1,467	114.7
Montana	18.8	1,503	155.9
New Mexico	14.9	792	44.0

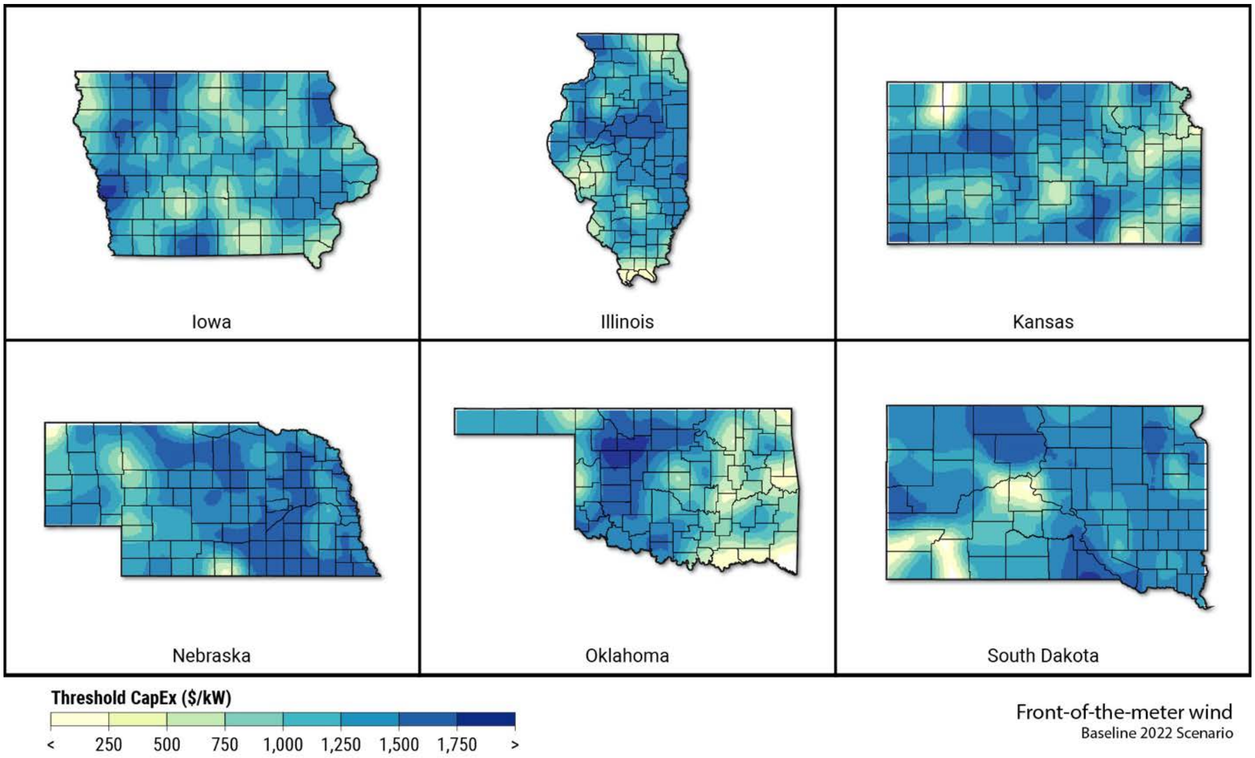


Figure 11. Front-of-the-meter wind threshold CapEx by county for the states with the largest economic potential; Baseline 2022 scenario

4.4.2 Behind-the-Meter Applications

The threshold CapEx is shown across the contiguous United States for behind-the-meter applications under the Baseline 2022 scenario in Figure 12. Figure 13 shows the same metric for the Baseline 2035 scenario. From these figures, we see that the Pacific and Northeast regions as well as some portions of the Great Plains, especially in Minnesota and other portions of the interior heartland, have higher threshold CapEx values. These data illustrate that it is a combination of good resource and high retail electricity prices that is expected to drive profitable behind-the-meter applications.

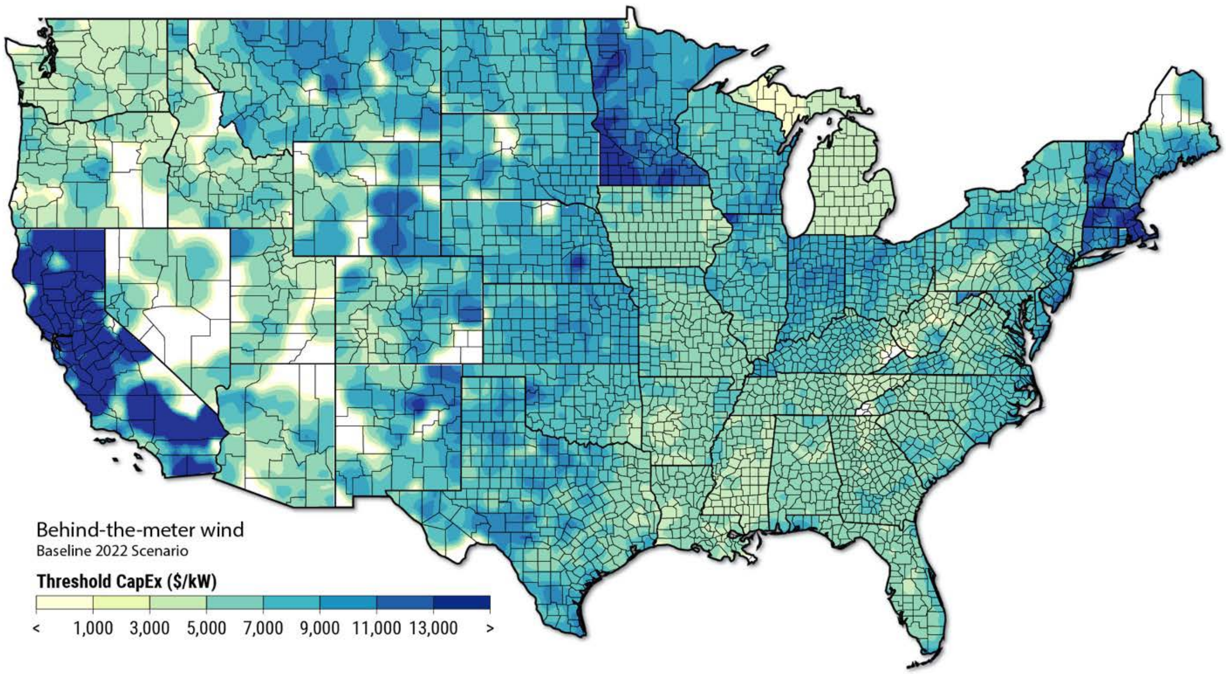


Figure 12. Behind-the-meter wind threshold CapEx by state and county; Baseline 2022 scenario

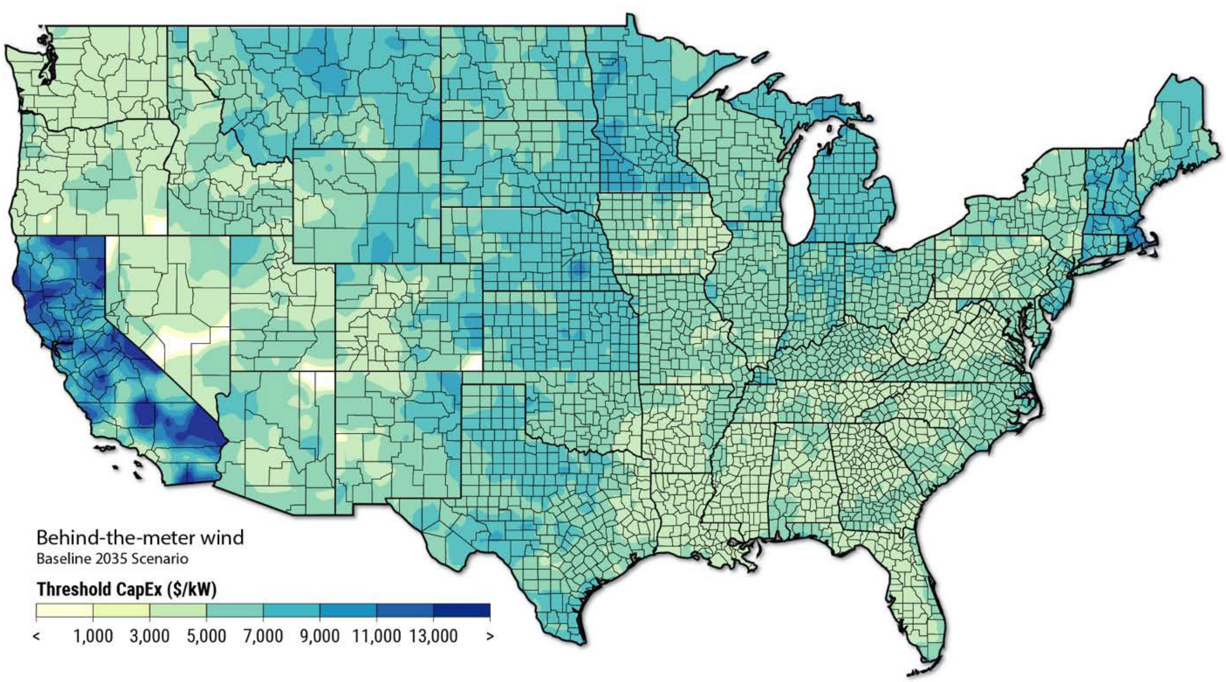


Figure 13. Behind-the-meter wind threshold CapEx by state and county; Baseline 2035 scenario

From the Baseline 2022 scenario, Table 5 presents the top 10 states in the contiguous United States ranked by economic potential. The 80th percentile threshold CapEx in the state is presented in the third column, followed by the technical potential in the fourth column. The economic potential is calculated using the same 2035 benchmark CapEx value presented in Section 4.2 of $4,353/kW in 2035.

Texas, Minnesota, Montana, Colorado, Oklahoma, and Indiana are the states with the highest economic potential (Table 5). Notably, it is not necessarily those states with the highest threshold CapEx values that tend to have the largest quantities of economic potential. This fact presents a dilemma for near- to midterm development regarding whether one should prioritize regions with fewer locations but higher threshold CapEx values or regions with lower threshold CapEx values but potentially more sites to develop. Figure 14 provides more granular information by identifying the counties within the states that have the highest economic potential.

Table 5. States With the Largest Economic Potential for Behind-the-Meter Applications (Baseline 2022 Scenario)

State	Economic Potential 2022 (GW)	80th Percentile Threshold CapEx ($/kW)	Technical Potential (GW)
Texas	188.9	8,114	257.1
Minnesota	74.0	12,650	74.6
Montana	69.0	9,136	71.4
Colorado	57.9	7,839	72.4
Oklahoma	56.9	6,972	122.1
Indiana	52.8	9,443	81.5
South Dakota	48.3	8,205	50.5
North Dakota	46.5	8,338	78.1
New Mexico	44.7	8,646	132.3
Kentucky	44.6	7,330	61.4

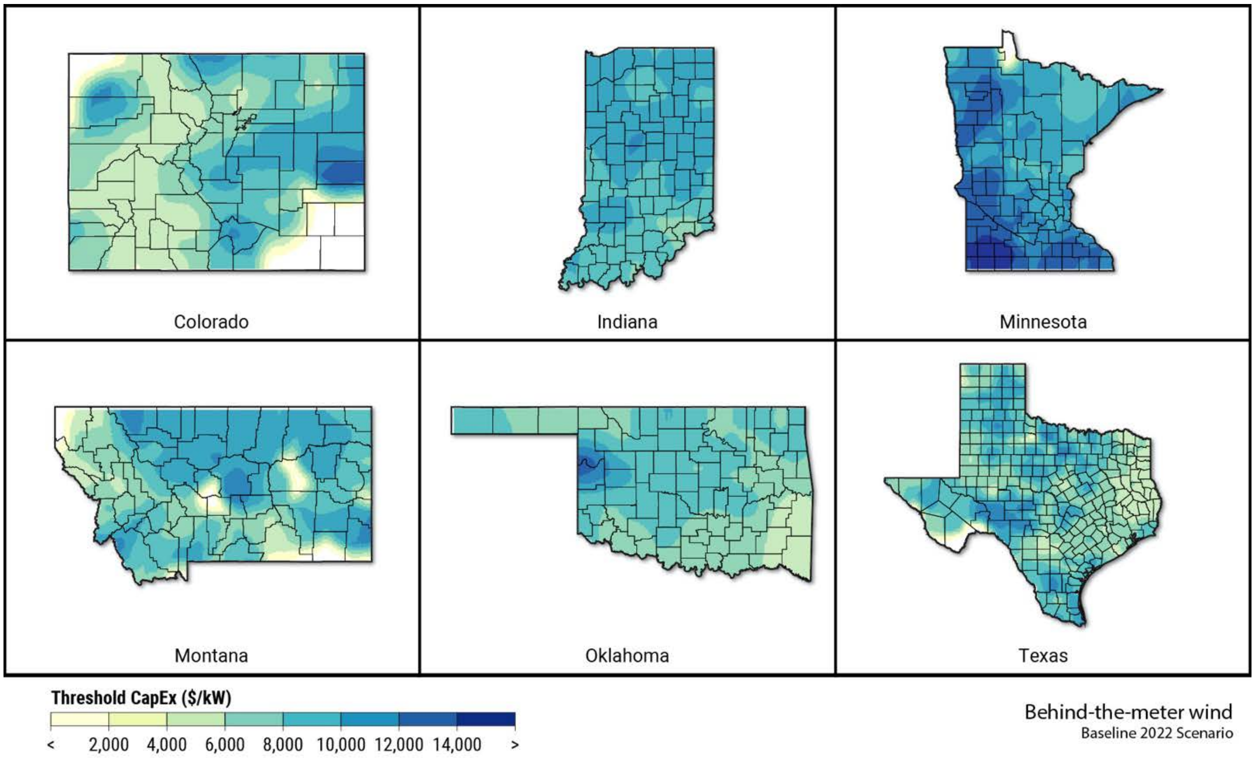


Figure 14. Behind-the-meter wind threshold CapEx by county for the states with the largest economic potential; Baseline 2022 scenario

4.4.3 Agriculture Land-Use Opportunities

Agricultural parcels tend to be well-correlated with a high-quality resource and abundant land. Not coincidentally, agricultural parcels are widely used for large-scale wind power plants, so it is natural that opportunities for distributed wind energy applications are also significant in these locales.

Table 6 and Table 7 identify states with the highest economic potential, for the Baseline 2022 scenario for behind-the-meter and front-of-the-meter applications, respectively, on agricultural land. These tables also identify the 80th percentile threshold CapEx values and technical potential values for these states. From Table 6 we observe that Texas, Montana, Minnesota, Colorado, Indiana, and North Dakota have the largest economic potential for behind-the-meter applications on agricultural land.

Table 7 shows that Oklahoma, Nebraska, Illinois, Kansas, Iowa, and South Dakota have the largest economic potential for front-of-the-meter applications in 2022 on agricultural lands. Figure 15 and Figure 16 provide deeper insight on the threshold CapEx values specific to counties within the states that have the largest economic potential for behind-the-meter and front-of-the-meter applications on agricultural land.

Table 6. States With the Largest Economic Potential for Behind-the-Meter Applications on Agricultural Land (Baseline 2022 Scenario)

State	Economic Potential 2022 (GW)	80th Percentile Threshold CapEx ($/kW)	Technical Potential (GW)
Texas	160.9	8,376	220.0
Montana	67.1	9,276	68.2
Minnesota	50.3	13,539	50.3
Colorado	45.9	6,760	56.9
Indiana	44.4	9,471	46.0
North Dakota	42.1	7,247	71.2
Oklahoma	41.1	8,127	98.8
South Dakota	38.0	8,123	39.1
Kansas	34.5	8,939	36.1
Illinois	28.1	7,484	35.0

Table 7. States With the Largest Economic Potential for Front-of-the-Meter Wind on Agricultural Land (Baseline 2022 Scenario)

State	Economic Potential 2022 (GW)	80th Percentile Threshold CapEx ($/kW)	Technical Potential (GW)
Oklahoma	102.8	1,698	198.8
Nebraska	56.8	1,725	268.7
Illinois	56.3	1,598	395.2
Kansas	46.6	1,600	221.6
Iowa	32.2	1,669	130.6
South Dakota	28.5	1,589	130.8
Pennsylvania	28.3	1,223	79.2
New York	21.5	1,470	84.4
Montana	18.8	1,503	155.9
New Mexico	14.9	354	24.1

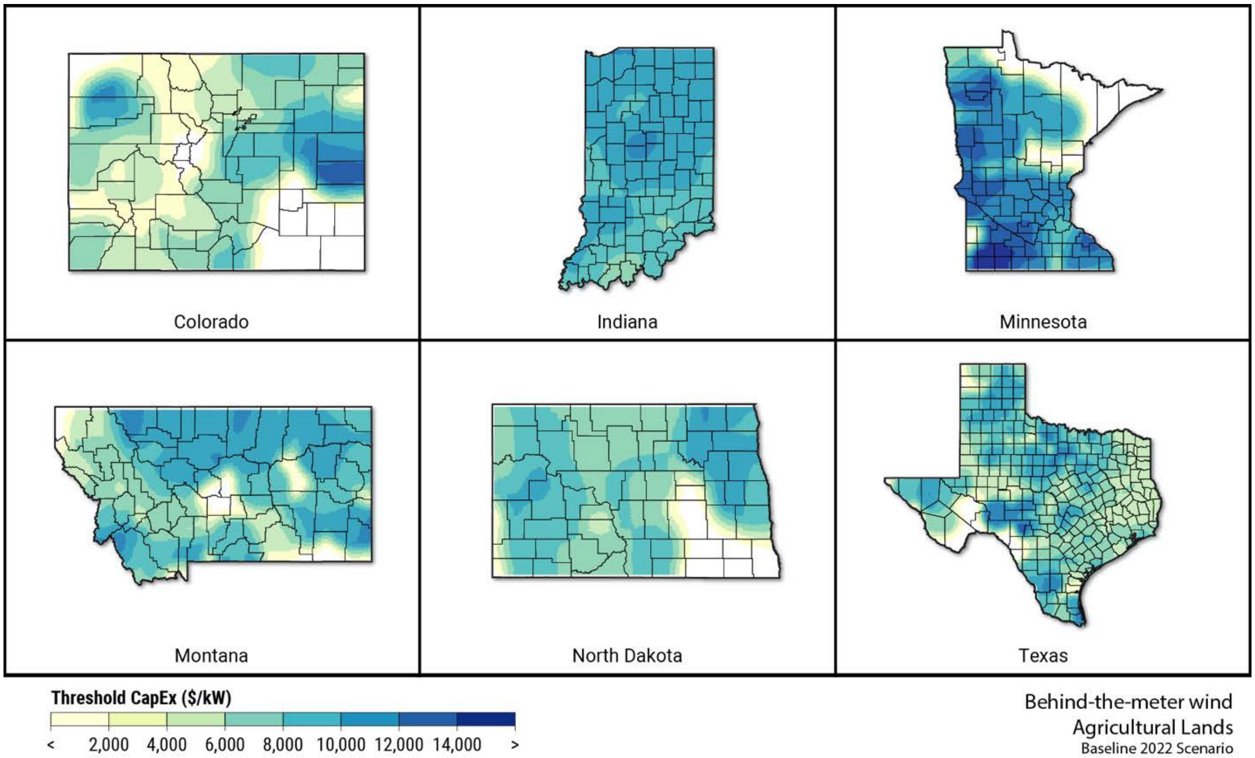


Figure 15. Threshold CapEx by county for states with the largest economic potential for behind-the-meter applications on agricultural land; Baseline 2022 scenario

Note: White spaces on these maps reflect the absence of the designated land type that is the focus of this section. Moreover, the interpolation method used due to sampling of parcels results in soft boundaries around those locations where the data for the applicable land type is present. Accordingly, the colored portions of these state maps are illustrative of the general vicinity of regions within these states that have higher or lower threshold CapEx values. However, additional site-specific analysis is required to discern precise locations for counties and parcels with a given threshold CapEx.

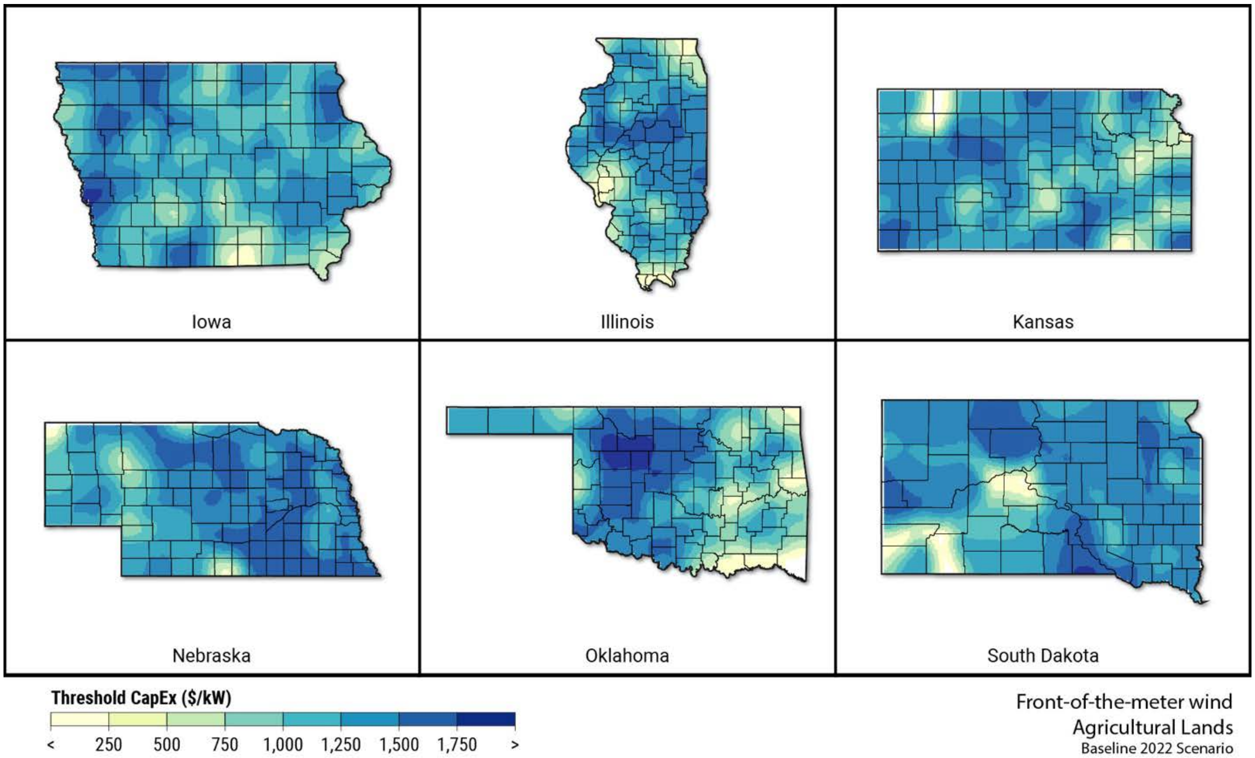


Figure 16. Threshold CapEx by county for states with the largest economic potential for front-of-the-meter applications on agricultural land, Baseline 2022 scenario

4.4.4 Commercial and Industrial Sector Opportunities

The commercial and industrial sector is another important market segment for distributed wind energy. It tends to have many relatively large electricity users, some of which are sensitive to electricity prices and their volatility. Moreover, industrial sites may be relatively accommodating for distributed wind energy systems from a siting and social acceptance perspective, potentially enabling a landowner to extract additional revenue from working land for front-of-the-meter applications. Distributed wind energy provides the opportunity for relatively fixed electricity prices, and the larger electricity users are sometimes able to take advantage of the economies-of-scale cost savings that might be available from deploying large, distributed wind turbines.

From the Baseline 2022 scenario, Table 8 identifies the states with the largest economic potential values for behind-the-meter applications on commercial and industrial parcels. This table also provides the 80th percentile threshold CapEx values for those states. Our results show that Kansas, Colorado, Texas, South Dakota, New Mexico, and Kentucky have the largest economic potential for behind-the-meter applications on commercial and industrial parcels.

Under our modeling assumptions, front-of-the-meter applications are not economic on commercial and industrial parcels. This finding is likely a result of the relatively small number of parcels, parcel size, and location of commercial and industrial lands, as well as relatively low modeled wholesale power rates for these locations. The threshold CapEx data presented in Table 9 show that the CapEx values would have to be reduced well below our benchmark CapEx value of $993/kW (for 2035) to realize these opportunities. Overall, this result is consistent with what we tend to see in practice, wherein commercial and industrial sector opportunities are often explored as behind-the-meter opportunities.

Figure 17 provides granular information on the threshold CapEx values by county for the states that have the highest economic potential for behind-the-meter applications. Overall, there are relatively fewer commercial and industrial land parcels than agricultural lands. Accordingly, the economic potential for behind-the-meter applications on commercial and industrial parcels is relatively smaller. Nevertheless, it remains significant in absolute terms at gigawatt scale. Moreover, with several states that have relatively high-threshold CapEx values, the sector could persist as a key segment of distributed wind energy for many years before saturating the market.

Table 8. States With the Largest Economic Potential for Behind-the-Meter Applications in the Commercial and Industrial Sectors (Baseline 2022 Scenario)

State	Economic Potential 2022 (GW)	80^{th} Percentile Threshold CapEx ($/kW)	Technical Potential (GW)
Kansas	2.2	9,047	2.2
Colorado	1.8	7,207	2.0
Texas	1.5	10,091	4.3
South Dakota	1.1	10,201	1.1
New Mexico	1.0	9,725	1.1
Kentucky	0.9	8,503	0.9
Nebraska	0.7	10,852	0.7
Minnesota	0.5	9,303	0.7
Illinois	0.5	8,700	11.6
North Dakota	0.5	5,962	0.6

Table 9. States With the Highest Threshold CapEx Values for Front-of-the-Meter Applications in the Commercial and Industrial Sectors (Baseline 2022 Scenario)

State	80th Percentile Threshold CapEx 2022 ($/kW)	Technical Potential (GW)
Nebraska	1,488	0.9
Texas	1,394	4.7
Illinois	1,364	14.0
South Dakota	1,327	0.7
New Mexico	1,121	1.0
Indiana	1,081	2.8
Utah	840	3.1
North Dakota	840	0.4
Colorado	706	1.6
Michigan	628	0.7

Figure 17. Threshold CapEx by county for states with the largest economic potential for behind-the-meter applications on commercial and industrial parcels; Baseline 2022 scenario

Note: White spaces on these maps reflect the absence of the designated land type that is the focus of this section. Moreover, the interpolation method used due to sampling of parcels results in soft boundaries around those locations where the data for the applicable land type is present. Accordingly, the colored portions of these state maps are illustrative of the general vicinity of regions within these states that have higher or lower threshold CapEx values. However, additional site-specific analysis is required to discern precise locations for counties and parcels with a given threshold CapEx.

4.4.5 Residential Sector Opportunities

Residential distributed wind energy provides landowners an alternative or complement to PV systems. Wind on residential land can also help counter increasingly high retail energy prices and demand for on-site power generation while leaving much of the surrounding land open to additional uses. The presence of policies like net metering and incentives like the ITC can make residential wind systems a cost-effective solution.

From the Baseline 2022 scenario, Table 10 details the states with the largest economic potential for behind-the-meter applications on residential parcels. This table also provides the 80th percentile threshold CapEx values for these states. States with the largest economic potential for behind-the-meter applications on residential land include New York, Minnesota, Kentucky, Texas, Oklahoma, and South Dakota. However, as observed previously, some states like California and Massachusetts have locations with notably high threshold CapEx values that could be worth exploring further for their potential for near-term projects. Figure 18 provides the threshold CapEx values by county for the states that have the largest economic potential for behind-the-meter applications on residential lands.

Under our modeling assumptions, front-of-the-meter applications are not economic on residential parcels; however, Table 11 includes those states with the highest threshold CapEx values and their respective technical potential for front-of-the-meter applications. In practice, it seems unlikely that front-of-the-meter installations on residential parcels will be a significant market segment. In principle, however, there are some large parcels denoted as residential, where midsize and large wind turbines could be sited, as evidenced by the technical potential results.

Table 10. States With the Largest Economic Potential for Behind-the-Meter Applications on Residential Land (Baseline 2022 Scenario)

State	Economic Potential 2022 (GW)	80th Percentile Threshold CapEx ($/kW)	Technical Potential (GW)
New York	18.7	7,071	39.6
Minnesota	17.9	12,781	18.3
Kentucky	16.3	6,527	28.4
Texas	15.6	6,990	21.3
Oklahoma	13.1	7,002	19.6
South Dakota	9.0	7,735	10.1
Arizona	8.8	6,383	11.0
Wisconsin	8.7	9,183	11.8
New Mexico	7.0	8,319	8.5
California	6.3	21,409	9.3

Table 11. States With the Highest Threshold CapEx Values for Front-of-the-Meter Applications on Residential Land (Baseline 2022 Scenario)

State	80th Percentile Threshold CapEx 2022 ($/kW)	Technical Potential (GW)
North Dakota	1,586	6.4
New York	1,441	28.8
Missouri	1,308	2.1
Michigan	1,140	2.2
Maryland	1,131	0.7
Arkansas	1,090	9.9
California	1,014	9.6
Texas	782	16.2
Nevada	636	1.6
Colorado	617	18.1

Figure 18. Threshold CapEx by county for states with the largest economic potential for behind-the-meter wind on residential land; Baseline 2022 scenario

Note: White spaces on these maps reflect the absence of the designated land type that is the focus of this section. Moreover, the interpolation method used due to sampling of parcels results in soft boundaries around those locations where the data for the applicable land type is present. Accordingly, the colored portions of these state maps are illustrative of the general vicinity of regions within these states that have higher or lower threshold CapEx values. However, additional site-specific analysis is required to discern precise locations for counties and parcels with given threshold CapEx.

4.4.6 Opportunities by Wind Turbine Size

In this section, we present results by wind turbine class and turbine size using the turbine classes defined in Appendix B. Results are then binned by residential turbines, which are defined as turbines with a capacity of less than 20 kW, commercial-size turbines with a capacity ranging from 20 kW to 100 kW, and midsize and large turbines with a capacity ranging from 100 kW to 1.5 MW.

While residential turbines (less than 20 kW) have the highest threshold CapEx values in California and Massachusetts, the economic potential for behind-the-meter residential wind turbines is largest in Texas, Minnesota, Montana, Oklahoma, Indiana, and Colorado (Table 12). Figure 19 provides more detailed data by showing counties with the high threshold CapEx values in those states with large economic potential. Based on these data, residential turbines have significant economic opportunities for behind-the-meter applications and locations that are economically viable in many regions. Residential wind turbines do not have significant potential in front-of-the-meter applications.

Commercial-size (20–100 kW) wind turbines in behind-the-meter applications have the highest economic potential in Colorado, Kentucky, Indiana, Alabama, Rhode Island, and Texas (Table 13). Figure 20 provides the threshold CapEx by county for the states that have the highest economic potential for commercial-size turbines. Although these results may seem counterintuitive based on historical wind deployments, commercial-size behind-the-meter applications require a relatively unique customer type with a moderately sized load coupled with a moderately sized parcel. When focusing narrowly on this sector, there are some outcomes that may seem surprising, but for this specific commercial-size behind-the-meter potential, these are the locations that our analysis shows have the best mix of conditions to use this size turbine. Commercial-size wind turbines do not have significant potential in front-of-the-meter applications.

Table 14 identifies states with the highest economic potential for midsize (100 kW–1 MW) and large (greater than 1 MW) turbines in behind-the-meter applications. There is limited significant potential for midsize and large turbines in behind-the-meter applications, so these locations are not mapped. Table 15 identifies states with the highest economic potential for large turbines in front-of-the-meter applications. Because front-of-the meter economic potential is heavily dominated by midsize and large turbines, Figure 9, Figure 10, and Figure 11, which focus on threshold CapEx for all front-of-the-meter applications, also illustrate the locations with the highest threshold CapEx for midsize and large turbines in front-of-the-meter applications. Small turbines (i.e., residential and commercial size) are generally not selected for front-of-the-meter applications in the model because it optimizes and sites the largest possible wind turbine in each parcel.

Table 12. States With the Largest Economic Potential for Residential Wind Turbines in Behind-the-Meter Applications (Baseline 2022 Scenario)

State	Economic Potential 2022 (GW)	80th Percentile Threshold CapEx ($/kW)	Technical Potential (GW)
Texas	188.3	8,145	254.6
Minnesota	74.0	12,653	74.6
Montana	69.0	9,142	71.3
Oklahoma	56.9	6,972	122.1
Indiana	51.6	9,452	54.2
Colorado	50.5	7,776	64.8
South Dakota	48.3	8,205	50.5
North Dakota	46.5	8,338	78.1
New Mexico	44.7	8,646	132.3
Kentucky	43.0	7,188	59.5

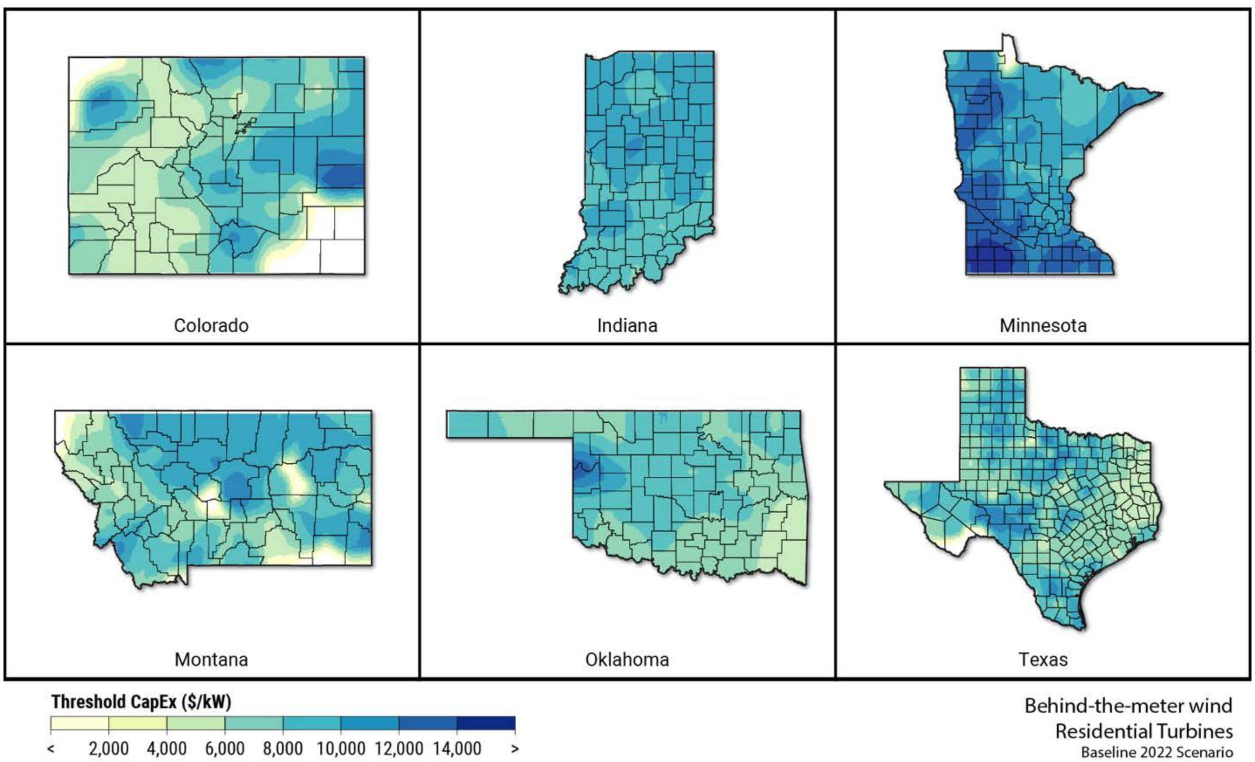


Figure 19. Threshold CapEx by county for states with the largest economic potential for residential turbines in behind-the-meter applications; the Baseline 2022 scenario

Table 13. States With the Largest Economic Potential for Commercial-Size Turbines in Behind-the-Meter Applications (Baseline 2022 Scenario)

State	Economic Potential 2022 (GW)	80th Percentile Threshold CapEx ($/kW)	Technical Potential (GW)
Colorado	7.3	11,196	7.6
Kentucky	1.6	9,972	2.0
Indiana	1.3	9,292	21.2
Alabama	0.6	6,372	0.7
Rhode Island	0.3	7,475	0.3
Texas	0.3	5,958	0.7
Kansas	0.2	10,589	0.2
North Carolina	0.1	6,468	0.9
Illinois	0.1	8,672	0.1

Figure 20. Threshold CapEx by county for states with the largest economic potential for commercial-size turbines in behind-the-meter applications; Baseline 2022 scenario

Note: White spaces on these maps reflect the absence of the designated land type that is the focus of this section. Moreover, the interpolation method used due to sampling of parcels results in soft boundaries around those locations where the data for the applicable land type is present. Accordingly, the colored portions of these state maps are illustrative of the general vicinity of regions within these states that have higher or lower threshold CapEx values. However, additional site-specific analysis is required to discern precise locations for counties and parcels with a given threshold CapEx.

Table 14. States With the Largest Economic Potential for Midsize and Large Wind Turbines in Behind-the-Meter Applications (Baseline 2022 Scenario)

State	80th Percentile Threshold CapEx ($/kW)	Technical Potential (GW)	Economic Potential 2022 (GW)	Economic Potential 2035 (GW)
Massachusetts	9,006	1.3	1.3	1.3
Ohio	6,033	0.6	0.6	0.6
Texas	3,163	1.7	0.3	0.6
Kansas	6,021	0.3	0.3	0.3

Table 15. States With the Largest Economic Potential for Midsize and Large Wind Turbines in Front-of-the-Meter Applications (Baseline 2022 Scenario)

State	Economic Potential 2022 (GW)	80th Percentile Threshold CapEx ($/kW)	Technical Potential (GW)
Oklahoma	103.9	1,700	199.9
Nebraska	56.8	1,727	267.5
Illinois	56.7	1,603	408.5
Kansas	46.6	1,623	220.1
Iowa	32.7	1,697	126.8
South Dakota	28.5	1,585	136.4
Pennsylvania	28.3	1,246	77.8
New York	21.5	1,472	108.7
Montana	18.8	1,504	155.8
New Mexico	14.9	792	44.0

4.5 Results for Energy Equity

Here, we explore opportunities for distributed wind energy in disadvantaged communities using the Baseline 2022 scenario results. Disadvantaged communities are identified as census areas with a high risk for environmental hazards and/or areas that include high proportions of low-income households (see Appendix F for a detailed description of the criteria used to identify disadvantaged communities).[17] In these communities, distributed wind offers at least two relevant opportunities. First, depending on local economics and policy, distributed wind could alleviate energy burden by providing lower cost and potentially more stable electricity to consumers. Second, distributed wind could bolster electricity system reliability in these regions.

[17] Our definition of disadvantaged communities is based on Energy Justice (EJ) Indexes from the Environmental Protection Agency's EJ Screen and Brownfield Sites (EPA, by census block group) and the National Renewable Energy Laboratory's REPLICA data set (by census tract). We acknowledge that these definitions are dynamic and evolving at the present time and our results may not be directly comparable to similar studies that rely on different definitions.

The results are presented by application—front of the meter and behind the meter—and are focused on distributed wind. Distributed solar results are presented in Appendix F.

4.5.1 Front-of-the-Meter Opportunities in Disadvantaged Communities

Disadvantaged communities represent 43% of all parcels where front-of-the-meter wind applications can be sited within the contiguous United States. Although front-of-the-meter distributed wind may not be applicable for many disadvantaged communities, our state-level results highlight some promising potential. The states with the highest economic potential in these disadvantaged communities are presented in Table 16. Likewise, the specific areas with the most promising opportunities in disadvantaged communities are highlighted in Figure 21. These data are also paired with the average energy burden statistics for disadvantaged communities to correlate distributed wind potential with relatively higher or lower levels of energy burden. Notably, these regions in each of these states have a much higher average energy burden than the national average of 2.9% (Ma et al. 2019). States with the highest economic potential in disadvantaged communities include Oklahoma, Illinois, Kansas, New Mexico, Nebraska, and Montana.

Table 16. States With the Largest Economic Potential for Front-of-the-Meter Applications in Disadvantaged Communities (Baseline 2022 Scenario)

	Economic Potential 2022 (GW)	80^{th} Percentile Threshold CapEx ($/kW)	Technical Potential (GW)	Average Energy Burden for DACs in each State (% Income)
Oklahoma	**58.5**	**1,688**	**78.8**	**18**
Illinois	16.9	1,621	86.1	15
Kansas	15.4	1,612	73.1	20
New Mexico	14.9	1,086	28.4	16
Nebraska	8.6	1,721	36.0	19
Montana	7.7	1,511	57.0	21
New York	4.8	1,342	6.2	14
South Dakota	4.5	1,613	40.5	18
Missouri	4.2	1,544	71.8	20
Iowa	3.4	1,744	18.2	16

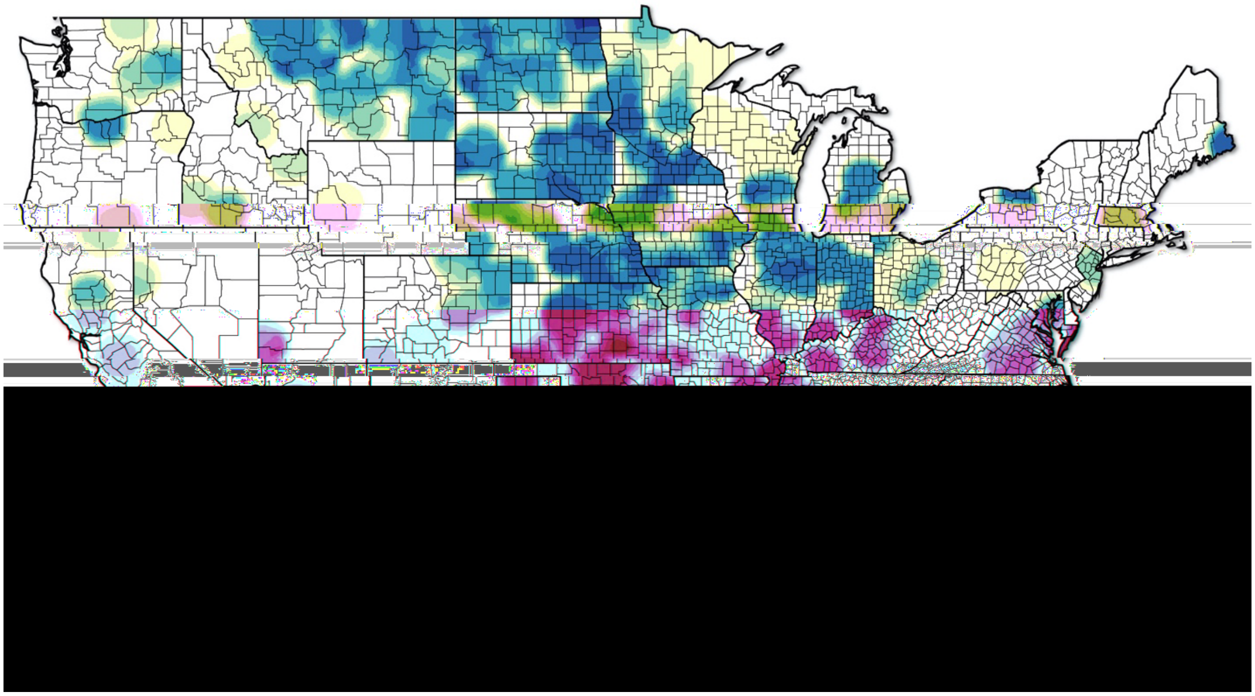


Figure 21. Threshold CapEx by state and county for front-of-the-meter wind in disadvantaged communities; Baseline 2022 scenario

4.5.2 Behind-the-Meter Opportunities in Disadvantaged Communities

At the national level, disadvantaged communities represent 47% of all parcels where behind-the-meter applications can be sited. By comparing threshold CapEx values among communities by state, we discovered that some states have more promising opportunities for disadvantaged communities than others. The states with the highest economic potential in these communities are presented in Table 17. These data are also paired with the average energy burden statistics for disadvantaged communities within each state to correlate distributed wind potential with relatively higher or lower levels of energy burden. The areas with the most promising opportunities for distributed wind in disadvantaged communities are highlighted in Figure 22. States with high economic potential include Texas, Montana, New Mexico, California, South Dakota, and Kansas. By 2035, these results are expected to vary based on changes in policy and potentially projected value of DERs.

Table 17. States With the Largest Economic Potential for Behind-the-Meter Applications in Disadvantaged Communities (Baseline 2022 Scenario)

	Economic Potential 2022 (GW)	80th Percentile Threshold CapEx ($/kW)	Technical Potential (GW)	Average Energy Burden for DACs in each State (% Income)
Texas	61.3	7,444	96.4	15
Montana	45.1	9,313	46.6	21
New Mexico	33.5	8,274	108.6	16
California	26.0	21,301	43.1	9
South Dakota	21.3	8,058	21.4	18
Kansas	15.9	9,201	16.0	20
Illinois	13.9	7,656	15.1	15
Kentucky	13.7	7,323	22.8	18
North Dakota	12.8	8,130	22.9	17
New York	12.0	6,719	30.0	14

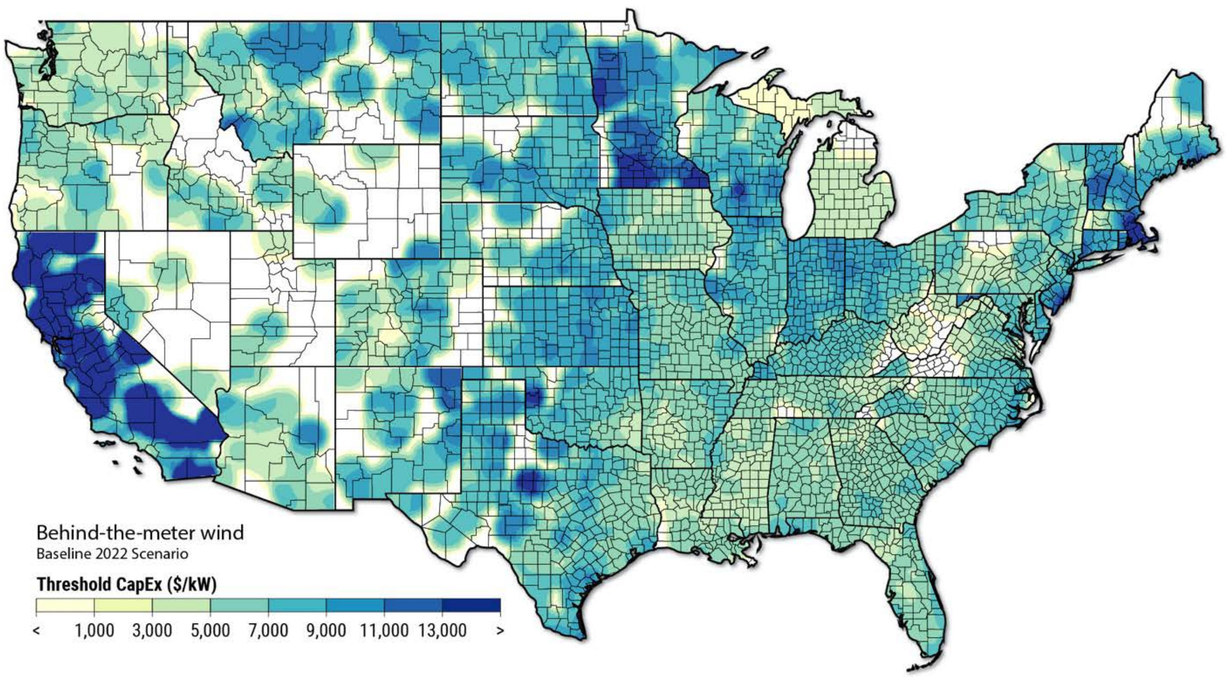


Figure 22. Threshold CapEx by state and county for behind-the-meter wind in disadvantaged communities; Baseline 2022 scenario

4.5.3 Intersection With Communities That Have a Population of 10,000 and Smaller

As a local resource, distributed wind has the potential to support rural communities' clean energy and energy independence goals. The bipartisan Infrastructure and Jobs Act also prioritizes and provides funding for activities that bolster energy and environmental protection in rural and remote communities with populations of 10,000 or less (DOE 2022b). Although definitions for communities of 10,000 or less vary, the intersection of windy land across broad swaths of rural America suggest the potential for distributed wind to support the administration's focus there as well as their focus on clean energy. This is particularly true in the Midwest and Heartland regions, where distributed wind's economic potential is also high. Locations in the Northeast and portions of the Mountain West are also indicative of many opportunities to use distributed wind in service of community-based energy goals.

5 Opportunities for Emissions Offset

Distributed wind energy has the potential to reduce emissions as a result of installing a behind-the-meter or front-of-the-meter system at a given location and reducing the net demand that must be served by centralized, utility-scale fossil generation. As with the previous sections, these results can be divided by specific dimensions, such as technology, application, and scenario. The avoided emissions results here will focus on state-level results of distributed wind in the Baseline 2035 scenario.

The primary metric for these results is avoided carbon dioxide (CO_2) emissions in kilograms (kg), which is a measure of the estimated potential reduction in CO_2 emissions that could be achieved by installing a distributed wind or solar system in a given location. The reduction potential reflects an intersection of several key variables in the analysis: generation potential (i.e., resource quality), DER siting ability, and marginal emission rate, as well as the correlation between periods of high marginal emissions rates and generation patterns, which inform the magnitude of reduction potential as well as the resulting spatial trends.

One key input to the emissions offset analysis is the long-run marginal emission rate (LRMER), which is the emission rate of the generation that a marginal change in load would be served by. The estimates for avoided CO_2 emissions (kg) are a result of the product between the annual generation (MWh) and the LRMER value (kg/MWh)—thus, the results presented here represent the *potential* for each distributed wind system to provide avoided emissions, as the model does not address deployment considerations. Values for LRMER are obtained from the NREL Cambium model (Gagnon et al. 2020), which provides these data by location, year, and scenario (see Appendix A.6.3 for a detailed discussion of Cambium and its usage in this emissions analysis).[18] The Cambium Midcase scenario from the 2020 model was selected to align with the Baseline 2035 scenario. It should be noted that estimates for the avoided CO_2 emissions potential by state shown below represent the annual avoided emissions from a high-performing wind turbine (defined here as the 95th percentile values for wind turbines by state). As the avoided emissions are based on the marginal grid conditions provided by Cambium's LRMER metric, it is not possible to provide state-level, cumulative estimates of emissions reduction potential from distributed wind. For more information on the limitations of Cambium, and applying its results, see Appendix A.6.3.

5.1 Front-of-the-Meter Applications

Figure 23 shows the highest (95th percentile) potential avoided CO_2 emissions estimates (kg) by state for front-of-the-meter applications. As observed in the threshold CapEx results, the locations that have the highest emissions offset potential generally coincide with regions of good wind resource. However, the addition of a key variable in the LRMER value by region also provides insight into the spatial trends that result from this emissions analysis. Figure 24 shows the raw Cambium LRMER data mapped by state for the Midcase scenario. States where the LRMER values are relatively high also appear to have a close relationship with the estimates of

[18] Since the development of the model used in this analysis, the Cambium model and associated data have been updated (compare Gagnon et al. [2020] and Gagnon et al. [2021]). Updates in the latest version of Cambium have been made to how marginal grid emissions are calculated. The results here do not reflect these updates, but future work in this space could take advantage of improved LRMER estimates for carbon emission offset potential.

avoided emissions. In particular, Montana, North Dakota, Kansas, Oklahoma, and Nebraska display higher emissions offset potential and reflect the favorable intersection of good wind resource and high LRMER values. The magnitude of these offset emissions estimates is also much larger relative to the behind-the-meter wind values—this larger magnitude is directly due to the larger average wind system size that is observed for front-of-the-meter applications.

Figure 23. Estimated annual carbon dioxide emissions reduction potential for the power system for front-of-the-meter wind under the Baseline 2035 scenario

Figure 24. Long-run marginal emission rate by state under the Cambium Midcase scenario

Note: Although these emissions rates data and the annual reduction in emissions shown in Figure 23 are shaded similarly, their scales are different, as would be expected when considering emissions rates relative to actual estimated emissions reduction potentials.

5.2 Behind-the-Meter Applications

Figure 25 shows the highest (95th percentile) of potential avoided CO_2 emissions estimates (kg) by state for behind-the-meter applications. For these applications, we observe more nuanced trends in emissions offset potential, though these results still demonstrate a close relationship with the raw Cambium LRMER data (Figure 24). Because behind-the-meter wind also has a stricter siting ability than front-of-the-meter wind, Figure 25 also inherently represents areas where behind-the-meter wind can be more favorably sited. This multidimensional intersection results in elevated emissions offset potential in Kentucky, North Carolina, Indiana, Utah, and Rhode Island. The magnitude of these offset emissions is relatively small compared to those in the front-of-the-meter wind results by approximately two orders of magnitude, which is primarily due to the smaller average system size (and thus, generation) that behind-the-meter applications exhibit.

Figure 25. Estimated annual carbon dioxide emissions reduction potential for the power system for behind-the-meter wind under the Baseline 2035 scenario

6 Discussion and Conclusions

This report seeks to highlight opportunities for distributed wind energy in the context of increased deployment of wind energy of all types: land-based, offshore, and distributed. We provide new insights on preferred regions for distributed wind energy applications including behind- and front-of-the-meter applications. We inform the degree to which these regions may be able to provide compelling economic returns for project owners and the relative quantities of distributed wind potential at varying levels of economic viability. We also identify locations to focus current efforts that might elevate the contribution of the distributed wind energy sector today and in the years to come, as the world increasingly relies on wind energy as a foundational component of the 21st century energy system.

Overall, we find that the United States has a substantial quantity of economic potential for distributed wind, nearly 1,400 GW in 2022. This amount equates to more than half of the nation's annual electricity consumption and is enough to provide millions of households with clean power. With the potential for several terawatts (TW) more of profitable wind generation by 2035, distributed wind energy can be a significant contributor to the nation's electricity supply. Notwithstanding this massive potential, the economics of distributed wind are highly sensitive to policies, especially those that impact project-level costs. For example, if current tax credits and net-metering policies expire as scheduled, economic potential is estimated to drop between 2022 and 2035. However, if current tax credits and policies are extended and strategically expanded, economic potential increases by more than 80% for behind-the-meter applications and by a factor of nearly nine for front-of-the-meter applications. Of course, economic potential that reflects basic profitability given specific benchmark costs is a necessary but not sufficient condition to drive widespread deployment of distributed wind energy systems. Competing with other distributed energy resources through lower costs and driving down life cycle risks and customer acquisition costs are also important to foster customer uptake and use. Given competition between DERs, including wind and solar, close examination and analysis of proposed policy provisions and their applicability to distributed wind is also important if stakeholders seek to convert distributed wind energy's potential into deployment.

Opportunities to convert this potential into clean energy generation tend to be correlated with the intersection of several key analysis variables, including wind resource quality, prevailing electricity rates for behind-the-meter applications and wholesale power rates for front-of-the-meter applications, and siting availability. Focusing on our results for the Baseline conditions in 2022, economic potential for behind-the-meter distributed wind applications is deepest in the Midwest and heartland. The top six states with the largest quantities of economic potential include Texas, Minnesota, Montana, Colorado, Oklahoma, and Indiana. For this scenario, these six states alone total approximately 500 GW of economic potential. Focusing on development opportunities in these states would provide a large pool of economically viable projects to consider. More generally, behind-the-meter opportunities are compelling in sites that possess a combination of windy land and higher retail electricity rates. As a result, favorable conditions also exist in pockets of the Pacific and Northeast regions. Economic potential for front-of-the-meter distributed wind in the Baseline 2022 scenario is also deepest in the Midwest and heartland; the top six states with the largest quantities of economic potential include Oklahoma, Nebraska, Illinois, Kansas, Iowa, and South Dakota. For this scenario, these states alone total over 300 GW of economic potential, again providing a deep pool of economically viable project sites to be considered.

When evaluating 2022 opportunities by land type, agricultural lands provide the largest opportunity. More specifically, these lands make up 70% of the total 2022 economic potential for behind-the-meter wind and 97% of the total 2022 economic potential for front-of-the-meter wind. Focusing on the top six states alone, the economic potential on agricultural lands is more than 400 GW for behind-the-meter wind and more than 300 GW for front of the meter. These results demonstrate the sizable economic potential available on agricultural lands in the heartland today as well as significant opportunities for agricultural decarbonization and revenue diversification. Commercial and industrial lands—though comprising a significantly smaller share of the total economic potential—also provide significant gigawatt-scale opportunities, especially for behind-the-meter applications. Kansas, Colorado, Texas, South Dakota, New Mexico, and Kentucky each have more than 900 MW of behind-the-meter economic potential in 2022 on commercial and industrial lands. Similarly, behind-the-meter economic potential on residential lands provides tens of gigawatts of economic potential in several states; states with the largest potential include New York, Minnesota, Kentucky, Texas, Oklahoma, and South Dakota.

Shifting to potential based on wind turbine size, the 2022 geographic distribution of economic potential by turbine size correlates strongly with the broader trends in economic potential for both front- and behind-the-meter distributed wind applications. Notably, however, 2022 economic potential for residential-sized wind turbines (<20 kW) in behind-the-meter applications is more than 40 GW in each in the top 10 states. Economic potential in 2022 for commercial-sized wind turbines (20 to 100 kW) in behind-the-meter applications ranges from 100 MW to more than 7 GW in Colorado (the top state), indicating a smaller but still significant market for commercial-sized turbines. Residential- and commercial-sized wind turbines are not expected for front-of-the-meter applications in significant numbers. Today's 2022 economic potential for midsize and large turbines (100 kW to multimegawatts) is largest for behind-the-meter applications in Massachusetts, Ohio, Texas, and Kansas, with each state having several hundred megawatt-to-gigawatt levels of potential; front-of-the-meter applications are best for this size class in Oklahoma, Nebraska, Illinois, Kansas, Iowa, and South Dakota, where each state has more than 30 GW of economic potential. Close examination of states and counties where midsize and large turbines have significant potential in behind- and front-of-the-meter systems could yield new opportunities for deployment.

States with the highest economic potential for front-of-the-meter distributed wind energy in disadvantaged communities include Oklahoma, Illinois, Kansas, New Mexico, Nebraska, and Montana. Among these states there are more than 120 GW of economic potential. States with the highest economic potential for behind-the-meter distributed wind energy in disadvantaged communities include Texas, Montana, New Mexico, California, South Dakota, and Kansas. Among these states there are more than 200 GW of economic potential. Based on their distribution and frequency across the country, there is strong correlation between favorable states for distributed wind and disadvantaged communities. This is particularly true in the Midwest and Heartland but includes coastal regions with high threshold CapEx values. Based on these outcomes, locations where distributed wind could provide energy and environmental benefits to rural and remote disadvantaged communities are likely abundant.

Overall, the potential for distributed wind energy is significant both today and into the future, providing profitable pathways to clean energy futures for homes, businesses, municipalities, and communities. Moreover, by reducing reliance on the nation's already constrained transmission network, distributed wind can foster clean energy development in parallel with transmission expansion. These opportunities may be even more compelling when these systems are combined with solar and batteries to maximize their value to the grid. Given strong economics, focused efforts could foster deployment across the nation, providing a compelling motivation for continued work to enhance distributed wind energy's competitiveness with other distributed energy resources and to increase its attractiveness for consumers as an energy technology serving both end users and communities in realizing their ambitions for low-cost, abundant clean energy.

References

Bergey Windpower. n.d. "Bergey Excel 15." http://bergey.com/wp-content/uploads/Excel-15_Spec-Sheet_Rev.-1_4.7.17.pdf.

Bhaskar, Parangat, and Tyler Stehly. 2021. *Technology Innovation Pathways for Distributed Wind Balance-of-System Cost Reduction*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-77452. https://www.nrel.gov/docs/fy21osti/77452.pdf.

Brown, Maxwell, Wesley Cole, Kelly Eurek, Jon Becker, David Bielen, Ilya Chernyakhovskiy, Stuart Cohen, et al. 2020. *Regional Energy Deployment System (ReEDS) Model Documentation: Version 2019*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-74111. https://www.nrel.gov/docs/fy20osti/74111.pdf.

Clark, Caitlyn E., Aaron Barker, Jennifer King, and James Reilly. 2022. *Wind and Solar Hybrid Power Plants for Energy Resilience*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5R00-80415. https://www.nrel.gov/docs/fy22osti/80415.pdf.

Cole, Wesley, Sean Corcoran, Nathaniel Gates, Trieu Mai, and Paritosh Das. 2020. *2020 Standard Scenarios Report: A U.S. Electricity Sector Outlook*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77442. https://www.nrel.gov/docs/fy21osti/77442.pdf.

Database of State Incentives for Renewables & Efficiency (DSIRE). 2021. "Database of State Incentives for Renewables & Efficiency." NC State University. Accessed September 1, 2021. http://www.dsireusa.org/.

Distributed Wind Energy Association. 2020. "Distributed Wind Energy Association's Support of Energy Justice: Black Lives Matter." Accessed January 30, 2022. https://distributedwind.org/distributed-wind-energy-associations-support-of-energy-justice-black-lives-matter/.

Fingersh, L., M. Hand, and A. Laxson. 2006. *Wind Turbine Design Cost and Scaling Model*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-500-40566. https://www.nrel.gov/docs/fy07osti/40566.pdf.

Gagnon, Pieter, Will Frazier, Elaine Hale, and Wesley Cole. 2021. *Cambium Documentation: Version 2021*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-81611. https://www.nrel.gov/docs/fy22osti/81611.pdf.

Gagnon, Pieter, Will Frazier, Elaine Hale, and Wesley Cole. 2020. *Cambium Documentation: Version 2020*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-78239. https://www.nrel.gov/docs/fy21osti/78239.pdf.

Gagnon, Pieter, Robert Margolis, Jennifer Melius, Caleb Phillips, and Ryan Elmore. 2016. *Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65298. https://www.nrel.gov/docs/fy16osti/65298.pdf.

Lantz, Eric, Benjamin Sigrin, Michael Gleason, Robert Preus, and Ian Baring-Gould. 2016. *Assessing the Future of Distributed Wind: Opportunities for Behind-the-Meter Projects*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-67337. https://www.nrel.gov/docs/fy17osti/67337.pdf.

Lopez, Anthony, Trieu Mai, Eric Lantz, Dylan Harrison-Atlas, Travis Williams, and Galen Maclaurin. 2021. "Land Use and Turbine Technology Influences on Wind Potential in the United States." *Energy* 223(May): 120044. https://doi.org/10.1016/j.energy.2021.120044.

Ma, Ookie, Krystal Laymon, Megan Day, Ricardo Oliveira, Jon Weers, and Aaron Vimont. 2019. *Low-Income Energy Affordability Data (LEAD) Tool Methodology*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-74249. https://www.nrel.gov/docs/fy19osti/74249.pdf.

National Renewable Energy Laboratory. 2020 "2020 Annual Technology Baseline." Golden, CO: National Renewable Energy Laboratory. https://atb.nrel.gov/

National Renewable Energy Laboratory. 2021 "2021 Annual Technology Baseline." Golden, CO: National Renewable Energy Laboratory. https://atb.nrel.gov/.

Northern Power Systems. 2019. "NPS 100C-24." https://www.nps100.com/wp/wp-content/uploads/2019/10/brochure-NPS-100C-24_ed2019_light_ENG.pdf

OpenEI. 2020. "Utility Rate Database." Accessed July 21, 2020. https://openei.org/wiki/Utility_Rate_Database.

Orrell, Alice C., and Nikolas F. Foster. 2016. *2015 Distributed Wind Market Report*. Richland, WA: Pacific Northwest National Laboratory. PNNL-25636. https://www.energy.gov/sites/default/files/2016/08/f33/2015-Distributed-Wind-Market-Report-08162016_0.pdf.

Orrell, Alice, Kamila Kazimierczuk, and Lindsay Sheridan. 2021. *Distributed Wind Market Report: 2021 Edition*. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. DOE/GO-102021-5620. https://www.energy.gov/sites/default/files/2022-01/distributed-wind-market-report-2021-full-report-v2.pdf.

Pacific Northwest National Laboratory. n.d. "Distributed Wind Data." Accessed January 30, 2022. https://wind.pnnl.gov/dw_download/logon.aspx.

Ramdas, Ashwin, Kevin McCabe, Paritosh Das, and Benjamin Sigrin. 2019. *California Time-of-Use (TOU) Transition: Effects on Distributed Wind and Solar Economic Potential*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-73147. https://www.nrel.gov/docs/fy19osti/73147.pdf.

Sigrin, Benjamin, Michael Gleason, Robert Preus, Ian Baring-Gould, and Robert Margolis. 2016. *The Distributed Generation Market Demand Model (dGen): Documentation*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65231. http://www.nrel.gov/docs/fy16osti/65231.pdf.

Stehly, Tyler, Philipp Beiter, and Patrick Duffy. 2020. *2019 Cost of Wind Energy Review*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-78471. https://www.nrel.gov/docs/fy21osti/78471.pdf.

U.S. Department of Energy. 2022a. "How Energy Justice, Presidential Initiatives, and Executive Orders Shape Equity at DOE." January 3, 2022. Accessed January 30, 2022. https://www.energy.gov/diversity/articles/how-energy-justice-presidential-initiatives-and-executive-orders-shape-equity.

U.S. Department of Energy. 2022b. "Rural Opportunity Tour Fact Sheet." April 11, 2022. https://www.energy.gov/articles/rural-opportunity-tour-fact-sheet.

U.S. Energy Information Administration. 2021. "How much of U.S. energy consumption and electricity generation comes from renewable energy sources?" Accessed February 8, 2022. https://www.eia.gov/tools/faqs/faq.php?id=92&t=4.

United States Environmental Protection Agency. 2020a version. EJSCREEN. https://www.epa.gov/ejscreen/download-ejscreen-data.

United States Environmental Protection Agency. 2020b version. Brownfields. https://www.epa.gov/frs/geospatial-data-download-service.

USBuildingFootprints. Github. https://github.com/microsoft/USBuildingFootprints.

Vestas. 2000. "V47-660 kW With OptiTip and OptiSlip." https://sti2d.ecolelamache.org/ressources/EE/premiere/TP/serie%202/Vestas_V47.pdf.

The White House. 2021. "Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies." https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.

Wiser, Ryan, and Mark Bolinger. 2016. *2015 Wind Technologies Market Report*. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. DOE/GO-10216-4885. https://www.energy.gov/sites/default/files/2016/08/f33/2015-Wind-Technologies-Market-Report-08162016.pdf.

Wiser, Ryan, Mark Bolinger, Ben Hoen, Dev Millstein, Joe Rand, Galen Barbose, Naïm Darghouth, et al. 2021. *Land-Based Wind Market Report: 2021 Edition*. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. DOE/GO-102021-5611. https://www.energy.gov/sites/default/files/2021-08/Land-Based%20Wind%20Market%20Report%202021%20Edition_Full%20Report_FINAL.pdf.

Zinaman, Owen, Alexandra Aznar, Carl Linvill, Naïm Darghouth, Timon Dubbeling, and Emanuele Bianco. *Grid-Connected Distributed Generation: Compensation Mechanism Basics*. National Renewable Energy Laboratory. NREL/BR-6A20-68469. https://www.nrel.gov/docs/fy18osti/68469.pdf.

Appendix A. Methodology

This section explains the constraints on where energy systems are sited (e.g., canopy cover, slope, setback factors, exclusion areas, and so on) and how they are sized (e.g., rooftop area, land parcel size, annual load, and so on), as well as how an optimal system is selected based on factors like the parcel attributes, the resource potential of the site, the technology specifications, and the compensation mechanisms or revenue streams applicable in that region.

A.1. Sampling

We selected a random sample of parcels for each model run. The sample excluded parcels from Alaska, Hawaii, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands and only included those with available land-use information. Although the parcel data set from which the sample was drawn has good coverage across counties (Figure A1), it does not feature uniform coverage throughout the United States. However, methods were applied to ensure that every county in the contiguous United States (CONUS) has at least one parcel represented in the model.

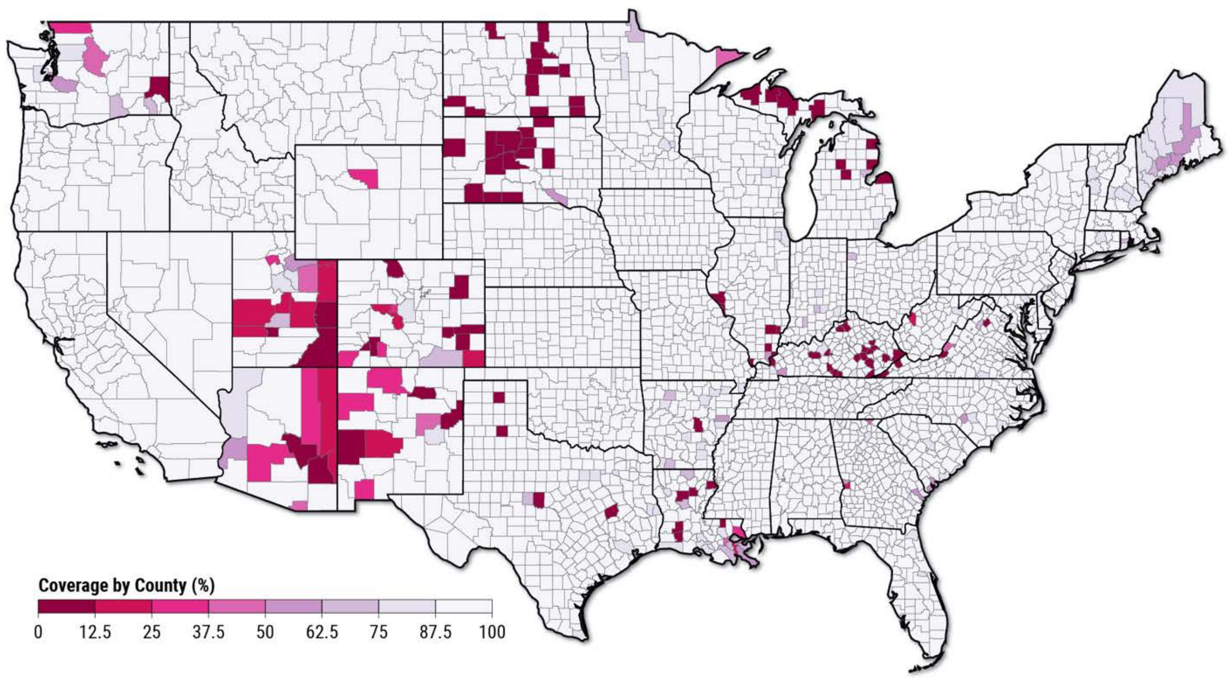


Figure A1. Overall parcel coverage by county

A.2. Statistical Weights

To make national estimates from model results, we calculated statistical weights for each parcel sampled in the model. This process involves assigning a value to each parcel that identifies the number of parcels represented by the sampled parcel.

Parcels are weighted by land-use category defined in the Lightbox parcel data analytics platform[19]: residential, commercial, industrial, agricultural/rural, recreational,

[19] https://www.lightboxre.com/

exempt/government, vacant, and miscellaneous. The total number of parcels for each of these land-use categories for every *state* was calculated using the entire parcel data set, and likewise, the total number of parcels for each of the land-use categories for every state was calculated for the sample parcels. The totals for the entire parcel data set are divided by the totals of the sample data set to obtain the weights for each sample parcel. The weights are then scaled by the percent of null land-use values in each state, as well as the total number of missing parcels in the national parcel data set.

The sum of all weights in the sample data is equal to the total number of parcels in the CONUS. Therefore, weights from the sample data are used to inform national estimates of results produced in the model by multiplying the values of output variables by the sample weights.

To avoid overrepresenting rural parcels (that are typically larger than urban parcels), the area or amount of land that makes up each parcel is not considered during the weighting process. Selecting larger sampling sizes also avoids overrepresenting parcels after applying weights.

A.3. System Siting

Siting constraints are imposed on the random parcel samples before these parcels are considered for system siting. Certain constraints, such as exclusions, determine the available land area of the parcels (once they are removed), and other constraints, such as setback factors, determine the maximum system size that a parcel can site. Any parcel with a known development constraint, whether due to a certain land-use designation or physical characteristics, was excluded from the final random sample used in the model. This section outlines the types of constraints imposed during parcel selection into the random sample.

A.3.1. Exclusion Areas

Exclusions are categorized by land use, infrastructure, and physical attributes.

A.3.1.1 Exclusions by Land Use

The full Lightbox parcels data set identifies land-use type of each parcel. Several land-use types preclude development of distributed electricity generation. Table A1 provides the full list of such land-use types.

Table A1. Parcel Land-Use Types Excluded for Distributed Energy Resource Development

Airport and related
Boat slips, marina, yacht club (recreation/pleasure), boat landing
Cemetery (exempt)
Cultural, historical (monuments, homes, museums, other)
Federal property (exempt)
Fish camps, game club, target shooting
Forest (park, reserve, recreation, conservation)
Historical-private (general) Chemically contaminated
Irrigation, flood control
Marine facility/boat repairs (small craft or sailboat)
Military (office, base, post, port, reserve, weapon range, test sites)
Natural resources
Outdoor recreation: beach, mountain, desert
Park, playground, picnic area
Private preserve, open space, vacant land (forest land, conservation)
Public swimming pool
Rail (right-of-way and track)
Railroad and related
Recreational vehicles/travel trailers
Reservoir, water supply
Road (right-of-way)
Roads, streets, bridges
Timberland, forest, trees (agricultural)
Transportation
Waste land, marsh, swamp, submerged-vacant land
Water area (lakes, river, shore), vacant land
Watercraft (ships, boats, personal)
Wildlife (refuge)
Zoo

A.3.1.2. Exclusions by Infrastructure

We removed building footprints (using the USBuildingFootprints data set) from parcel geometries, such that the available land area for wind turbine siting was reduced.

A.3.1.3. Exclusions by Physical Attributes

Areas with a terrain slope greater than 20% were excluded (derived from the National Aeronautics and Space Administration's Shuttle Radar Topography Mission (90-meter spatial resolution).

A.3.2. Setback Factors

Following the removal of the exclusions mentioned earlier, we calculated the largest circle in the remaining polygon of the parcel to determine the maximum land area suitable for development. Using this new geometry, parcels were additionally filtered based on setbacks, canopy clearance, and the maximum parcel size requirement. Parcels that were not large enough to fit turbines once setbacks were considered were removed from the analysis. The value of the setback factor constraints for the baseline scenarios is shown in Table A2.

Table A2. Baseline Scenario Setback Factor Constraints

Constraint	Value
Required canopy clearance	10%
Canopy clearance static adder	12 meters
Blade height setback factor	1.1x turbine tip height[20]
Maximum parcel size requirement	1 million acres

A.4. System Sizing

System sizing for both wind and solar photovoltaics (PV) involves several factors, including the area available for system siting discussed in the previous section, technology-specific power density factors that relate the available area and the system capacity (e.g., kilowatt (kW) per square foot (ft^2) or kW/ft^2), and application-specific factors that dictate how behind-the-meter and front-of-the-meter systems can be sized. These data come from a variety of sources, including the National Renewable Energy Laboratory's (NREL's) Annual Technology Baseline (ATB) (NREL 2020) for many solar-specific attributes and front-of-the-meter wind attributes and a previous study on distributed wind (Lantz et al. 2016) for behind-the-meter wind sizing attributes. Parcels are eligible for behind-the-meter or front-of-the-meter systems based on their land-use type.

While there are technology-specific parameters that inform sizing for wind and solar PV separately, several variables are considered "global" and are required for the system sizing methodology regardless of the configuration of technology and application. For example, for behind-the-meter systems, the annual energy consumption of a given building within a parcel represents a maximum constraint—the inherent assumption being that the model does not size systems that offset greater than 100% of the on-site load. Another variable involves available area for system sizing—for rooftop PV, this includes the developable rooftop area (see Gagnon et al. 2016 and Sigrin et al. 2016); for ground-mounted front-of-the-meter solar PV and all wind applications, this includes the available area for system siting.

[20] Turbine hub height plus the blade length.

A.4.1. Distributed Wind

For behind-the-meter wind systems, the system siting methodology results in potentially several developable wind turbine configurations (there are 23 unique configurations of wind system sizes and hub heights) based on the available area in the parcel and the associated canopy cover attributes. The system sizing process for this application involves selecting the wind system size that most closely matches the annual energy consumption of the parcel, subject to a user-provided input that specifies a scalar multiple of this annual consumption value (e.g., a multiple of 1.0 sizes the system to offset as close to 100% of the parcel load; a value of 0.5 sizes the system to offset 50% of the load).

For front-of-the-meter wind systems, the model assumes that the largest possible wind system size will yield the greatest amount of revenue in the default model compensation scheme (see Sections 2.10 and 2.11). That is, it is assumed that a greater amount of generation can produce more revenue by bidding into wholesale markets, as represented via the Cambium framework. Thus, the front-of-the-meter system sizing process involves simply applies the largest possible wind turbine size for a given parcel.

A.4.2. Distributed Solar PV

For behind-the-meter solar PV systems, the NREL ATB (NREL 2021) provides current and future values of power density for rooftop PV systems. Thus, system sizing for this application involves simply taking the product between the year-specific density value (kW/ft^2) and the developable rooftop area for the building(s) in each parcel. The user may also specify a power density value in the configuration file, but the NREL ATB provides default values for the 2022 and 2035 scenarios. Like the behind-the-meter wind system sizing process, behind-the-meter solar PV systems are also constrained by the annual energy consumption of each parcel—systems are limited to offsetting 100% of the annual on-site load—but also have an additional constraint, which is the amount of developable rooftop area in each parcel. The behind-the-meter solar PV sizing process considers both constraints when calculating the optimal system size.

For front-of-the-meter solar PV systems, the assumed technology is a ground-mounted PV system—no rooftop systems are allowed in the front-of-the-meter framework. The available area for development as calculated in the system siting methodology is combined with a power density value for ground-mounted systems provided by the NREL Regional Energy Deployment System (ReEDS) model (Brown et al. 2020). The model also assumes that the front-of-the-meter, ground-mounted solar PV sizing process considers only south-facing systems and that the system tilt values are set to the latitude of the parcel.

A.5. Assigning and Scaling Load

We were not able to obtain load profiles for each parcel, so we assigned parcels a reference load profile based on its building type and climate zone, which impacts both the total annual load value and the shape of the profile. The selection of load profiles, which are obtained from RESSTOCK and COMSTOCK data, is a function of the Commercial Reference Building model associated with the parcel being characterized and its geographic location, which determines its climate zone. To improve the accuracy of the load profiles that are mapped to parcels, we also implement load scaling based on the square footage of the buildings on behind-the-meter parcels. First, we associate the land-use type with one of the reference load profiles via the parcel's

Commercial Reference Building model. Then, we obtain the floor area of the buildings located on the parcel using Lightbox parcel data, or, when that is not available, the parcel geometry from the Microsoft Buildings data set. When combined with the number of floors, we estimate the floor area. If neither Lightbox nor Microsoft Buildings have valid attributes for calculating the floor area of buildings located on the parcel, we simply assign the parcel a reference floor area that is associated with the reference load profile. We then scale annual load and maximum demand by the ratio of floor area associated with the parcel to the reference floor area from the Commercial Reference Building model. Note that if the parcel was assigned a reference floor area, the scaling factor is one.

A.6. Calculating Revenues

We used several tools and data sources to model revenue streams for valuing distributed energy resource (DER) generation. For behind-the-meter DERs, the amount of retail electricity costs offset by DER generation is calculated using retail tariffs from the Utility Rate Database (URDB). For front-of-the-meter DERs, the generated power that is sold to the grid at prevailing energy and capacity prices is derived from the Cambium model. The model relies on PySAM, which offers the full capabilities of NREL's System Advisor Model (SAM), to calculate cashflows and process retail tariffs for both behind-the-meter and front-of-the-meter systems. Lastly, the financing and leasing assumptions come from NREL's 2020 ATB. Because of this integration, the model inherited respective assumptions from each of these tools.

A.6.1. PySAM

The model relies directly on Pvwattsv7, Battery, Battery Tools, Utilityrate5, and Cashloan modules to evaluate technical and financial performance on an hourly basis over the system lifetime. Note that while the Distributed Wind Future Study scenarios explicitly several cost, performance, and financing parameters, the various PySAM models often require more detail than provided in the scope of these scenarios. Where these additional parameters do not have scenario-specific values, we elected to use the PySAM defaults as specified in the scenario input tables.

A.6.2. Utility Rate Database

Rate structures for behind-the-meter systems are based on data from the URDB (OpenEI 2020), an open-source database of actual rate data for most U.S. electric utilities. The Distributed Wind Future Study model currently relies on the rates data downloaded from the database in July 2020. Rate data stored in the database provide detailed information about various tariff parameters, including seasonal and time-of-use rates, rate tiers, demand charges, and other energy charges. The URDB contains numerous rates and covers most of the United States. Electric utilities are mapped to parcels based on the coincidence of the parcel location and the utility service territory. Often, several rates are considered applicable based on the parcel end-use sector (e.g., residential, commercial, industrial) and location—in these cases, the model can either perform a weighted random sample to select the single rate to use or an optimization can be performed to select the rate that minimizes the annual electricity bill based on the electric load and load profile.

A.6.3. Cambium

Cambium provides information on the marginal conditions for the power system in the continental United States in 2-year increments out to 2050, based on modeled conditions created by sequentially running a capacity expansion model (ReEDS) and a production cost model (PLEXOS).[21] In this model, Cambium is used as an input for front-of-the-meter revenue streams, as well as to provide estimates on how distributed wind generation might impact the operation of or emissions from the bulk power system by meeting demand locally. Cambium's "energy_cost_enduse" and "capacity_cost_enduse" metrics are assumed to be the energy and capacity prices that the front-of-the-meter system could access by discharging to the bulk power system, while the "co2_lrmer_enduse" metric is used to estimate emissions reduction potential (Gagnon et al. 2020). We use "enduse" values as opposed to corresponding "busbar" values, as the systems are located on the distribution system and can therefore help avoid losses from the transmission system.

Cambium outputs on marginal grid conditions are available for several standard scenarios including:

- Low renewable energy cost
- Midcase (which is used as this study's baseline)
- High-case renewable energy cost
- Low battery cost
- Low wind cost.

It is important to note that the revenues available to front-of-the-meter systems may underestimate the revenues the systems would see in real life as a result of the models driving Cambium. NREL's ReEDS capacity expansion model optimizes capacity investment decisions in generation and transmission to find the least-cost solution to meeting demand subject to various operating constraints. Because the ReEDS model optimizes these decisions, generation assets like utility-scale solar PV and wind will be built under the ReEDS model if they are the most cost-effective options. The *Distributed Wind Energy Futures Study* model therefore seeks to estimate the revenues available to front-of-the-meter generators from an already-optimized power system that endogenously considers wind and solar PV generation. In practice, if front-of-the-meter systems could adequately meet local energy and capacity needs, they might supplant the need for some of the bulk power generation modeled in ReEDS, thereby offsetting generation considered in the model and changing the marginal conditions of the power system that ultimately are informing our front-of-the-meter valuation.

Moreover, Cambium only considers energy and capacity value streams from the bulk power system and does not consider additional revenue streams that could be accessed by distributed generation such as distribution and transmission upgrade deferral or resilience. While these nonenergy and noncapacity values may be relatively small for most front-of-the-meter systems wherein there is little opportunity to reduce congestion or defer system upgrades, our model may be underestimating the potential value (and therefore revenues) some front-of-the-meter systems would see in more constrained portions of the distribution system.

[21] More information on the 2020 Cambium model used in this analysis can be found in Gagnon (2020).

Cambium provides data at an hourly resolution for geographic regions known as balancing areas based on how the ReEDS model divides the contiguous United States. For each front-of-the-meter system, its parcel was associated with the appropriate balancing area for the year in focus (2022 or 2035). The energy and capacity values ("energy_cost_enduse" and "capacity_cost_enduse," respectively) were applied directly from Cambium and passed as 8,760 values to the generator model. These values were used as the primary revenue input for front-of-the-meter systems, as well as to estimate the impact front-of-the-meter systems would have on bulk power system conditions.

To estimate the impact of behind-the-meter and front-of-the-meter systems on power system emissions, we used the long-run marginal emissions rate (LRMER) from Cambium ("co2_lrmer_enduse"). The LRMER seeks to capture how persistent changes in the load that the bulk power system must meet in a given hour and region would impact emissions from the power system, both by changing short-term operating decisions (e.g., turning down a coal plant in response to reduced net demand) and long-term investment decisions (e.g., reducing the capacity of a planned peaker plant in response to reduced peak afternoon demand). These impacts are examined from an operations perspective—which generators would be turned up or down in response to change in load—in the immediate term as well as from a long-term investment perspective—which new capacity additions would be over- or undersized in response to changing load patterns compared to the baseline. The LRMER was used to estimate reductions in power system emissions but first had to be adjusted. Instead of using the LRMER directly from Cambium, the LRMER values for each hour in the year of interest were normalized over the system's lifetime (25 years) using a discount rate of 6.4% to provide an estimate of the total lifetime emission reductions from persistently reducing demand in a given hour.[22]

As Cambium provides estimates of marginal grid values, and because this analysis relies exogenously on values from Cambium, there is an inherent limit on the ability to estimate the cumulative grid impacts from distributed wind using Cambium. If sufficient distributed generation is installed in a given region, it will change the marginal grid conditions that inform the values from Cambium. For instance, when providing estimates for emissions reduction potential for distributed wind in a given state, Cambium can only provide an estimate of the LRMER in a region under assumed marginal grid conditions; for example, that a coal generator is on the margin in a particular hour. The LRMER in this case is driven in part by the emissions rate of the coal generator, which would be turned down in response to demand being met locally by distributed wind.

Given sufficient distributed wind generation, however, a grid operator might decide to shut down the coal plant or turn down a more flexible generating unit instead if the coal plant is operating at its minimum stable level. If this happens, the reduction potential of the next distributed wind generator is no longer based on the coal plant's emission rate (Cambium's LRMER), but rather on the next generator to turn down in response to reduced net demand. Given these limitations, values for cumulative state-level emissions reduction potential cannot be accurately estimated from Cambium, although the values shown in this analysis provide a solid first approximation of emissions reductions for comparison across the country. Similarly, for the energy and capacity metrics used to inform front-of-the-meter valuation, sufficient distributed wind energy

[22] Based on conversations with the creator of the Cambium model.

deployment could influence the prices that such systems would see, and therefore their threshold capital expenditures.

The Cambium Data Viewer can provide additional information on the revenues modeled in the *Distributed Wind Energy Futures Study* for front-of-the-meter systems.

A.6.4. Annual Technology Baseline

The model relies on the 2020 ATB (NREL 2020) to determine the financing terms available to both behind-the-meter and front-of-the-meter systems. For behind-the-meter configurations, a host-ownership business model is assumed, wherein the customer owns and operates the DER system independently, accruing all costs, revenues, and financial incentives. The financial modeling includes a discounted cash flow analysis in each model year. The cash flows include operation and maintenance costs (capital costs are solved for in the breakeven cost framework), revenue from bill savings and the Investment Tax Credit, and tax considerations (i.e., Modified Accelerated Cost Recovery System for nonresidential agents). Electricity bill savings are based on hourly solar generation and electricity consumption profiles. For front-of-the-meter configurations, financing parameters are from the 2020 ATB "Moderate" scenario for utility-scale PV and land-based wind systems. All other required financial parameters (e.g., insurance rate, federal and state tax rates, property tax rate) that are not specified via ATB or the Distributed Wind Futures Study scenario are default PySAM values.

A.7. Compensation Mechanisms

This section covers how behind-the-meter and front-of-the-meter systems are compensated for generation that they export to the grid, as well as how behind-the-meter systems are charged for energy consumed from the grid. There are three main components of a compensation mechanism: the metering and billing arrangement, the sell rate design, and the retail rate design. Each of these components will be discussed in this section, both in their present form and any future possibilities that are supported by the model. Note that this discussion is specific to the in-model configuration of compensation mechanisms. For a more general overview of compensation mechanisms, see Zinaman et al. (2017).

A.7.1. Metering and Billing Arrangements for Behind-the-Meter Systems

Most applicable to behind-the-meter customers, metering and billing arrangements define how behind-the-meter consumption and generation are measured and billed. The three options for metering and billing in the model include net energy metering; buy all, sell all; and net billing. The arrangement that applies to each customer depends on state or utility policy. In our model, a list of net metering policies (and their expiration) by state and utility is curated from the Database of State Incentives for Renewables and Efficiency (2021). Often, these policies differ based on the system size and end-use sector, so these details are also captured from the database and applied in the model.

Another crucial element of the behind-the-meter compensation mechanism framework is the retail rate structure. Rate structures in our model are based on data from the URDB (see Appendix A.6.2). Behind-the-meter entities are assigned a "most likely" retail tariff from the URDB that is based on their location (utility) and end-use sector.

The final main element of the compensation mechanism framework for behind-the-meter entities, and closely related to the retail rate structure, is the sell rate. This defines the level of compensation that a system owner receives for electricity exported from the system to the grid (Zinaman et al. 2017). Sell rates are specific to both the utility and individual tariff, and therefore compensation depends both on the magnitude and time periods stated in the individual tariff. The tariff that each behind-the-meter entity is assigned as per the previously mentioned procedure will specify sell rates where applicable—all other behind-the-meter customers default to using the local wholesale price as the sell rate for excess generation.

The metering and billing frameworks described here generally remain static regardless of the focus year of the model simulation. The main exception is with regards to the net metering policies, wherein we model their expiration in one of two manners: 1) an explicit expiration date is specified by state or utility regulators or 2) no expiration date is given. In the former case, this date is set in the model and the state- or utility-specific policy shifts away from net metering at that time. In the latter case, we assume that the policy will expire 10 years after its inception date or by 2030, whichever comes first. In either case, the default policy is net billing—that is, a full net metering policy shifts to net billing upon expiration, or locations without an explicit net metering policy are set to a net billing framework.

A.7.1. Revenue for Front-of-the-Meter Systems

For front-of-the-meter customers, Cambium data are used to represent the sole revenue stream and primary compensation mechanism. Appendix A.6.3 describes Cambium and its role in our model in detail. Cambium data are also available by scenario and year, thus enabling the specification of revenues for front-of-the-meter entities through 2050.

Appendix B. Technology Cost and Performance Assumptions

This section discusses the model's assumptions about the current and future cost and performance parameters of distributed wind and solar photovoltaics. The rationale behind each of these assumptions is discussed in the following sections for each technology.

B.1 Distributed Wind

The model's assumptions for the current and future technology costs and performance of distributed wind energy are broken down by wind turbine class, as described here. Inputs to the model include hardware costs, balance-of-system (BOS) costs, variability in cost across space, and operations and maintenance (O&M) costs.

B.1.1 Wind Turbine Classes

A total of four representative turbines were used by this study to model the different scales of distributed wind turbines: residential, commercial, midsize, and large as shown in Table B1, including the attributes associated with each wind turbine class. The turbine performance and cost information of the reference turbine was adjusted to match the size of the representative turbine and will not specifically match information for the reference turbine.

Table B1. Wind Turbine Class Attributes

Turbine Class	Machine Rating (Kilowatts [kW])	Representative Size (kW)	Reference Turbine Model
Residential	≤ 20	20	Bergey Excel 15
Commercial	21–100	100	Northern Power Systems 100
Midsize	101–999	650	Vestas V-47
Large size	≥1,000	1,500	GE 1.5-MW

B.1.2 Current Turbine Performance

Table B2 and B3 describe the current performance of the representative distributed wind turbines used in this study.

Table B2. Current Performance of Residential and Commercial Wind Turbines

Parameter	Residential	Commercial	Sources
Machine rating (kW)	20	100	2019 Cost of Energy Review (Stehly et al. 2020)
Rotor diameter (meters [m])	12.4	27.6	
Hub height (m)	30	40	
Specific power (Watts/m^2)	166	167	
Max coefficient of power (CP)	0.4	0.5	Representative values for residential- and commercial-scale turbines (Bergey Windpower n.d.)
Max tip speed (meters per second [m/s])	95	75	
Max tip-speed ratio	9.7	8	

Table B3. Current Performance of Midsize and Large Wind Turbines

Parameter	Midsize	Large	Sources
Machine rating (kW)	650	1,500	Distributed Wind Balance of System Report (Bhaskar and Stehly 2021)
Rotor diameter (m)	70	107	2016 Futures Study (Lantz et al. 2016)
Hub height (m)	60	80	
Specific power (W/m^2)	169	167	
Max coefficient of power (CP)	0.5	0.5	Mid-Size: Vestas V47 Spec Sheet (Vestas 2000)
Max tip speed (m/s)	70	82	
Max tip-speed ratio	8	8	

B.1.3 Current Turbine Capital and O&M Costs

Table B4 and B5 describe the current capital and O&M costs of representative distributed wind turbines used in this study.

Table B4. Current Costs of Residential and Commercial Wind Turbines

Parameter	Residential	Commercial	Sources
Balance of systems (BOS) capital expenditures (CapEx) ($/kW)	$3,100	$1,770	Residential: Estimate from empirical data trends Commercial: Proprietary data collected by National Renewable Energy Laboratory (Lantz et al. 2016)
Turbine CapEx ($/kW)	$2,575	$2,530	
O&M ($/kW-year)	35	35	2016 Futures Study (Lantz et al. 2016)
Total losses (%)	11.50%	11.50%	Assume losses in 2019 Cost of Energy Review (Stehly et al. 2020)

Table B5. Current Costs of Midsize and Large Wind Turbines

Parameter	Midsize	Large	Sources
BOS CapEx ($/kW)	$869	$951	Distributed Wind Balance of System Report (Bhaskar and Stehly 2021)
Turbine CapEx ($/kW)	$1,897	$1,288	
O&M ($/kW-year)	$35	$35	2016 Futures Study (Lantz et al. 2016)
Total losses (%)	11.50%	11.50%	Assume losses in 2019 Cost of Energy Review (Stehly et al. 2020)

B.1.4 Future Wind Turbine Performance

Table B6 and B7 describe the future performance of the representative distributed wind turbines used in this study. The future performance and cost of the representative turbines is meant to articulate an average future turbine design. In the market, actual turbine sizes and the cost and performance of any specific turbine, best in class or worst in class, is expected to vary around the identified representative turbines and may also vary around the projected capital cost values reported in Section B.1.5 for any given scenario.

Table B6. Future Performance of Residential and Commercial Wind Turbines

Parameter	Residential	Commercial	Sources
Machine rating (kW)	20	100	Assuming future performance of 150 W/m2 (Lantz et al. 2016)
Rotor diameter (m)	13	29.1	
Hub height (m)	35	45	
Specific power (W/m^2)	150	150	
Max coefficient of power (CP)	0.4	0.5	Assuming no further improvements to machine's Cp Residential: Bergey Excel 15 Spec Sheet (Bergey Windpower n.d.). Commercial: NPS 100C-24 Specifications (Northern Power Systems 2019)
Max tip speed (m/s)	95	95	
Max tip-speed ratio	9.7	9.7	

Table B7. Future Performance of Midsize and Large Wind Turbines

Parameter	Midsize	Large Size	Sources
Machine rating (kW)	650	1,500	Assuming future performance of 150 W/m^2 (Lantz et al. 2016)
Rotor diameter (m)	74.3	112.8	
Hub height (m)	65	85	
Specific power (W/m^2)	150	150	
Max coefficient of power (CP)	0.5	0.5	Assuming no further improvements to machine's Cp Midsize: Vestas V47 Spec Sheet (Vestas 2000)
Max tip speed (m/s)	95	95	
Max tip-speed ratio	9.7	9.7	

B.1.5 Future Cost Projections

The future capital expenditure (CapEx) projections of distributed wind energy projects included four main scenarios: low deployment, reference/business-as-usual, high deployment, and breakthrough deployment. These four cost projection scenarios were obtained from the National

Renewable Energy Laboratory's (NREL's) behind-the-meter distributed wind futures study (Lantz et al. 2016). We used the same approach to modeling future cost projections as the 2016 behind-the-meter study, but for updated year 2020 costs obtained from NREL's *2020 Cost of Wind Energy* study (Stehly et al. 2022). See Table B8 for a summary of the 2016 behind-the-meter study's learning rates and assumptions used in this work, with CapEx values for 2020.

Table B89. Future Costs Learning Rates and Assumptions Obtained from Lantz et al. (2016) Coupled with Adjusted CapEx from 2020

Scenario	Future Costs Learning Rates and Assumptions
Low deployment	No change in capital cost relative to 2020
Reference case (business as usual)	Up to 45% reduction in capital cost by 2030 and 70% reduction by 2050, 4% reduction in O&M cost by 2030, and 10% reduction by 2050
High deployment	Up to 52% reduction in capital cost by 2030 and 71% reduction by 2050, 4% reduction in O&M cost by 2030, and 10% reduction by 2050
Breakthrough scenario	Up to 70% reduction in capital cost by 2030 and 75% reduction by 2050, 4% reduction in O&M cost by 2030, and 10% reduction by 2050

Figure B1 through Figure B4 summarize the 15-year look-ahead cost projections (2020–2035) under the four main scenarios. The future potential for a drop in CapEx values ($/kilowatt [kW]) for the residential, commercial, and midsize turbines is more significant than a large turbine project. However, like the 2016 behind-the-meter study, we implemented a price floor from the NREL 2021 ATB that applied all four scenarios to ensure that the project CapEx did not drop below projected costs for large wind farms which benefit from project level economies of scale that are not available to distributed applications. The biggest drivers for future cost reductions rely on the assumptions that high manufacturing volume will allow original equipment manufacturers to charge a lower overhead per turbine manufactured, cost-effective technological innovations in construction (or balance of plant) including innovations in crane/turbine erection technology and turbine foundations will be available. Additionally, costs associated with zoning, permitting, interconnection, and incentives (driven by fees and extended projects timelines) are also assumed to be streamlined (Bhaskar and Stehly 2021).

These future cost projections are meant to be estimates of what is possible under each of the four deployment scenarios. The boundaries created by the curves of each scenario show a range of possible project capital expenditures under each scenario, which we have further labeled to rank the likeliness of achieving these targets. Moreover, within these scenarios actual cost values will vary creating conditions for best-in-class and worst-in-class technology and costs even within the specific scenarios.

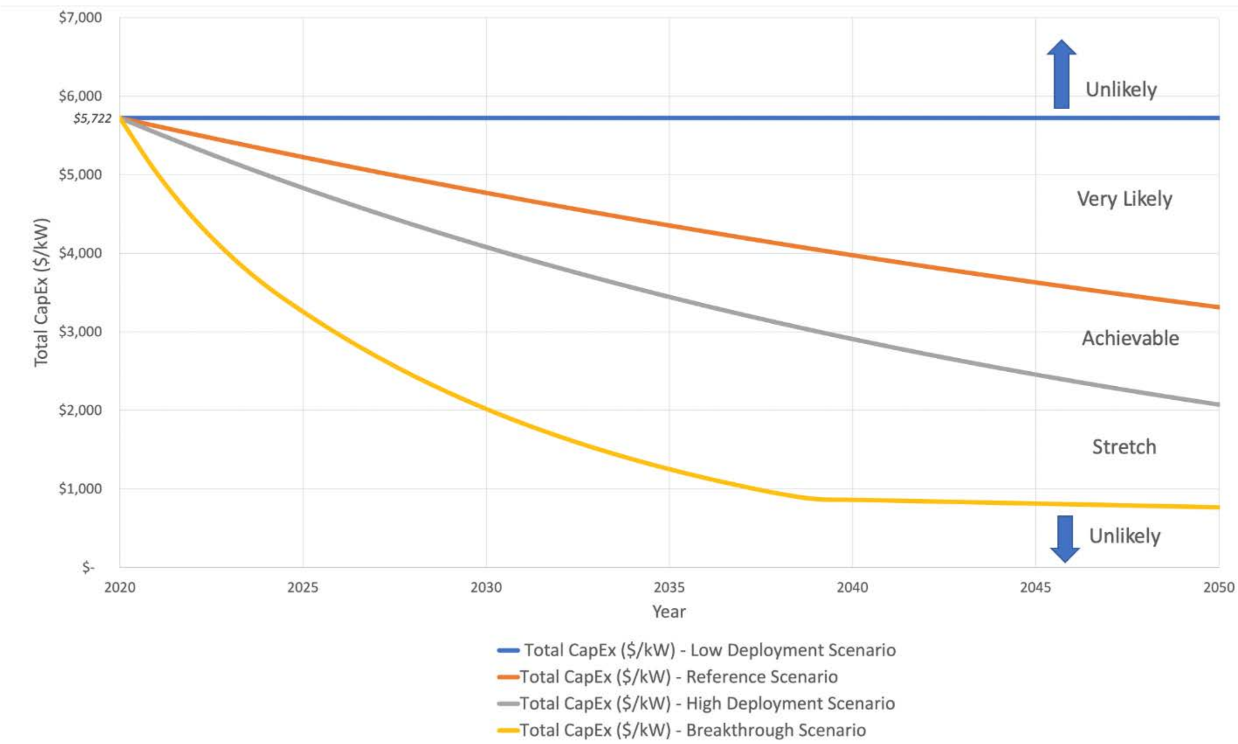


Figure B1. Residential-scale distributed wind project future total project CapEx ($/kW) projections

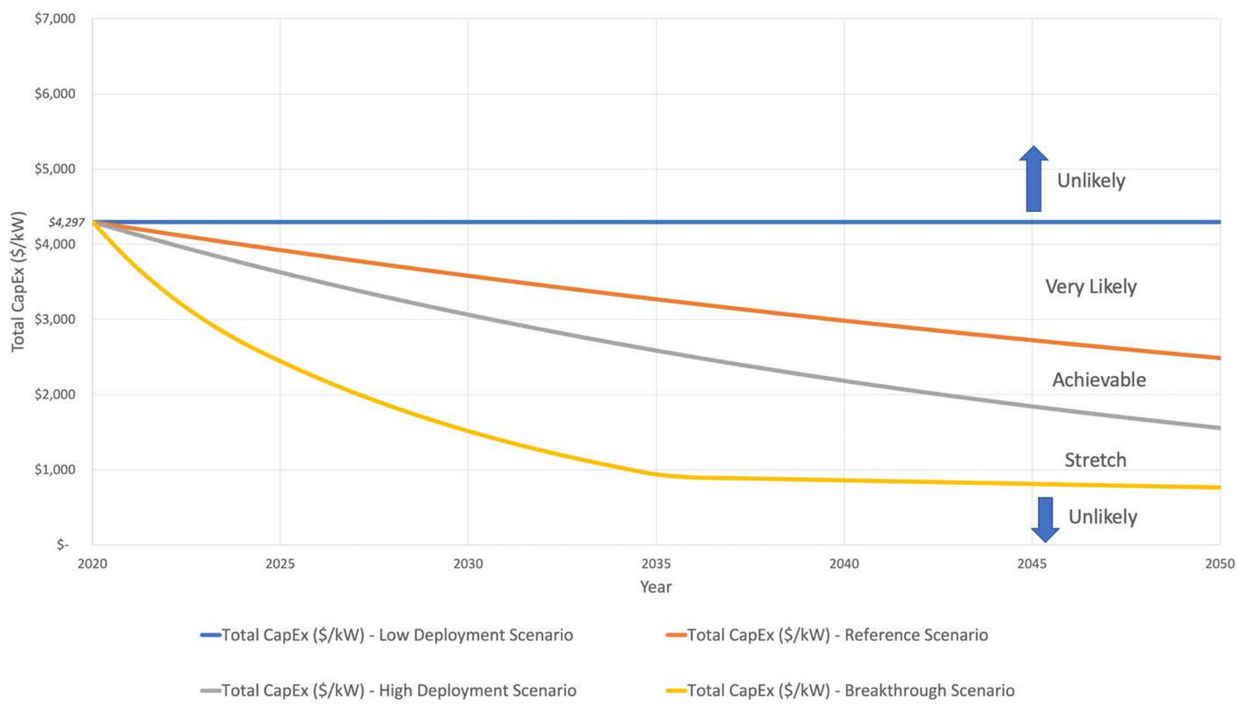


Figure B2. Commercial-scale distributed wind project future total project CapEx ($/kW) projections

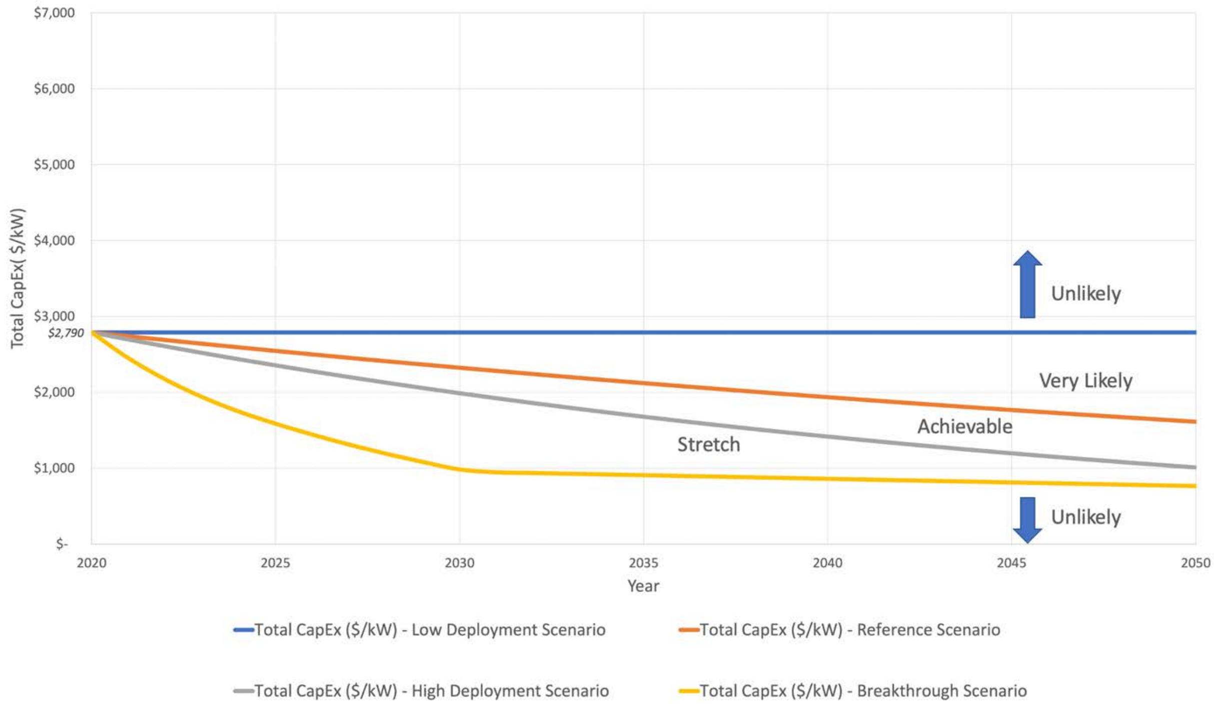


Figure B3. Midsize-scale distributed wind project future total project CapEx ($/kW) projections

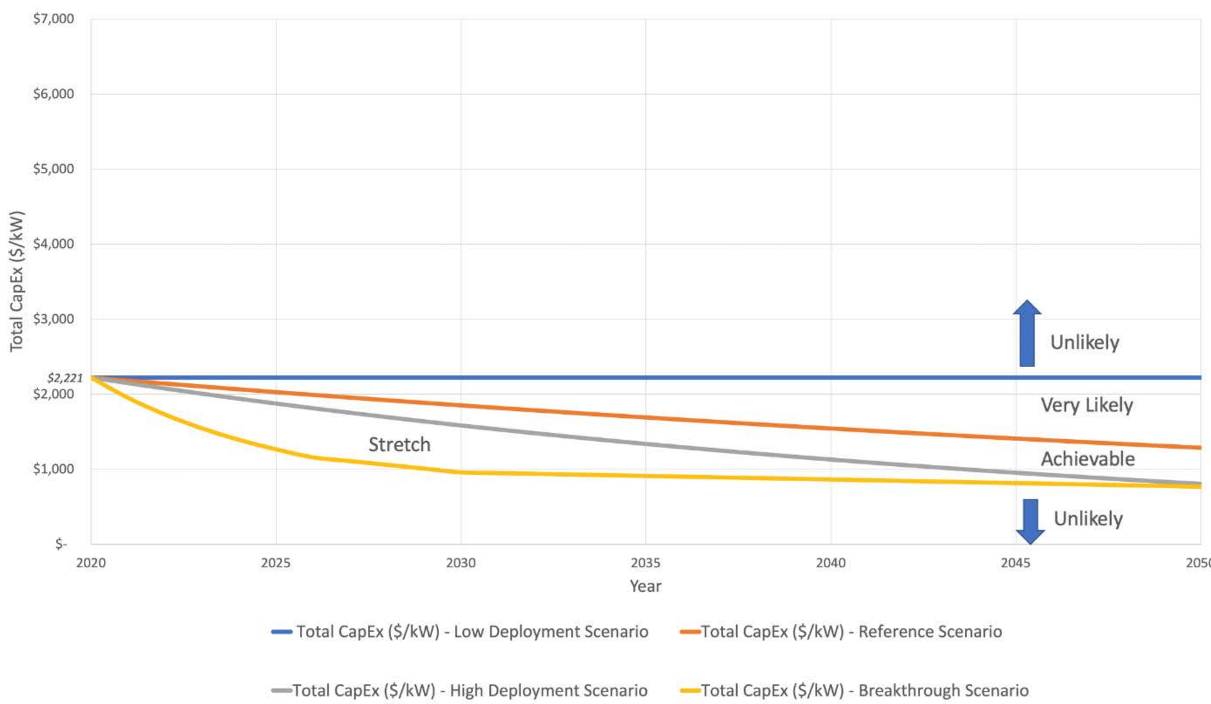


Figure B4. Large-scale distributed wind project future total project CapEx ($/kW) projections

B.1.6 Power Curves

This section summarizes the methodology behind the development of the power curves associated with each representative wind turbine class. NREL developed a new generic power curve (Figure B5) generator model for stall-regulated machines. The primary motivation for this model is to better represent the future potential of distributed wind in energy system modeling. Lantz et al. (2016) developed and implemented power curves that were synthesized using an average of the power curves of commercially available wind turbines in the market at that time. Although this approach provided a reasonable estimate for the technical performance of current machines, the averaged power curve method limited the ability to accurately estimate performance of future machines.

For this study, the generic power curve model requires five inputs: machine peak power (kW), rotor diameter (meters [m]), specific power (watts per square meter [W/m^2]), air density (kilograms per cubic meter [kg/m^3]), and turbine rotor coefficient of performance (Cp_{rotor}) versus turbine tip-speed ratio (TSR). The power curve estimation is split into the standard three regions (Regions I, II, and III), as presented in Figure B5 for a generic power curve. Power production in Regions II and III was calculated using the following logic:

> If tip speed > maximum tip speed → tip speed equals maximum tip speed
> If tip speed = maximum tip speed → calculate TSR and apply corresponding Cp

To calculate power in Region I, an additional calculated input, minimum revolutions per minute (rpm), is required in the model. The machine's minimum RPM is calculated using the TSR curve. Power production in Region I is then calculated using the following logic:

> If tip speed < minimum tip speed → tip speed equals minimum tip speed
> If tip speed = minimum tip speed → calculate TSR and look up corresponding Cp

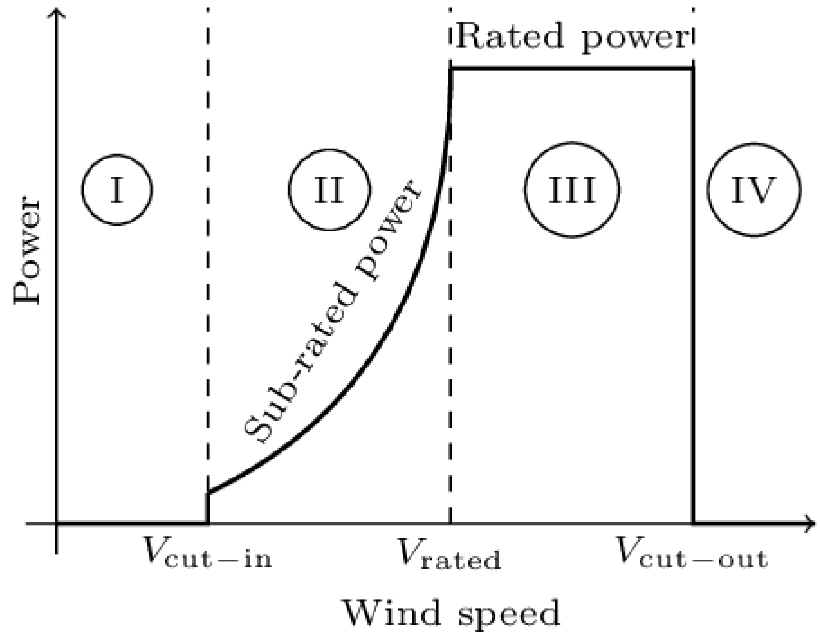
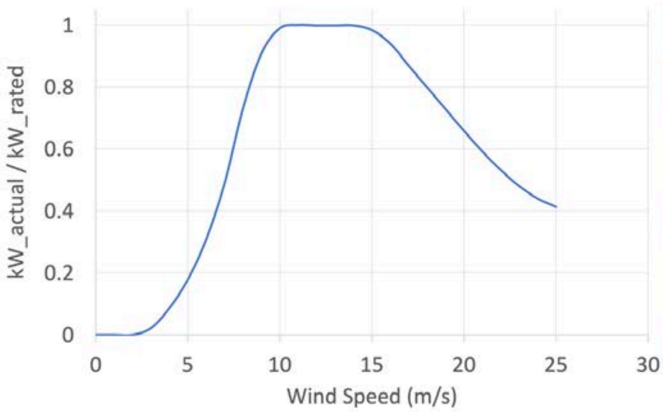


Figure B5. Generic power curve

For pitch-regulated machines, we use NREL's Cost and Scaling Model (CSM) (Fingersh, Hand, and Laxson 2006). Because of the complexity of the CSM, refer directly to Section 3.5 of Fingersh, Hand, and Laxson (2006) for a summary of the model's methodology.

B.1.7 Current Power Curves (Normalized)

Figure B6. Current normalized power curve for residential wind turbines



Input	Value
Rated Power (kW)	100
Rotor Diameter (m)	27.6
Max C_p	0.5
Max Tip Speed (m/s)	75
Max TSR	8

Figure B7. Current normalized power curve for commercial wind turbines (pitch-regulated)

Figure B8. Current normalized power curve for midsize wind turbines (pitch-regulated)

Figure B9. Current normalized power curve for large wind turbines (pitch-regulated)

B.1.8 Future Power Curves (Normalized)

Figure B10. Normalized power curve for residential wind turbines

Figure B11. Normalized power curve for commercial wind turbines (pitch-regulated)

Figure B12. Future normalized power curve for midsize wind turbines (pitch-regulated)

Figure B13. Future normalized power curve for large wind turbines (pitch-regulated)

Appendix C. Data and Mapping

Here, we describe the data we used and the mapping onto parcels. During the postprocessing phase, we grouped similar land-use types into relevant categories. This categorization makes it easier to draw conclusions about parcels that are similar in terms of the buildings located on-site, what they are used for, and their physical characteristics. Only land-use types that make up the top 95% of parcels by count were included in the groups for the sake of simplicity.

Table C1. Land-Use Type Groups Used for Analysis

Group Name	Land-Use Type	Description
Residential (single) (detached)	Residential (general) (single)	Single-family detached residences
	Single family residential	
	Single family residential (assumed)	
	Mobile/manufactured home (regardless of land ownership)	
	Modular/prefabricated homes	
	Mobile home park, trailer park	
	Seasonal, cabin, vacation residence	
Residential (single) (attached)	Condominium unit (residential)	Single-family attached residences
	Cooperative unit (residential)	
	Townhouse (residential)	
	Row house (residential)	
Residential (multiple)	Multifamily dwellings (generic, any combination 2+)	Multifamily residences
	Duplex (2 units, any combination)	
	Triplex (3 units, any combination)	
	Quadruplex (4 units, any combination)	
Commercial (general)	Office bldg (general)	Commercial
	Retail stores (personal services, photography, travel)	
	Auto repair (and related), garage	
	Commercial office (general)	
	Restaurant	
	Commercial building, mail order, show room (nonauto), commercial whse	
Industrial (general)	Warehouse (industrial)	Industrial
	Manufacturing (light)	

Group Name	Land-Use Type	Description
	Heavy industrial (general)	
	Heavy manufacturing	
Agricultural (general)	Farm (irrigated or dry)	Agricultural
	Misc. structures - ranch, farm, fixtures	
	Crop land, field crops, row crops (all soil classes)	
	Ranch	
	Dairy farm	
	Livestock parcel	
	Poultry farm (chicken, turkey, fish, bees, rabbits)	
	Truck crops (tobacco, cash crops)	
	Grain elevator	

Appendix D. Parcel Data Attributes

Here, we characterize the various attributes of the parcel data.

Table D1. Parcel Data Attributes

Field Name	Field Alias	Description
FIPS_CODE	FIPS code	Federal Information Processing Code for the state and Federal Information Processing Code for the county. First two digits are the state code and the last three digits are the county code.
PARCEL_APN	Assessor parcel number (APN)	Unique parcel APN derived from the parcel geometry. (note: may differ from unique APN derived from the tax assessor)
MASTER_PARCEL_APN	Master parcel APN	Master parcel APN. This is the master/main APN number associated with the primary parcel in a location where multiple parcels with identical geometry exist. This can occur where there are multiple taxable properties in a location (e.g., condos, timeshares, mobile home parks).
MULTI_TAXAPN_FLAG	Duplicative tax APN flag	Indicates multiple or split parcel sales (e.g., when a sale occurs that includes multiple parcels).
SITE_DIRECTION	Site direction	Directional prefix portion of a property address where a physical property resides (e.g., "N" in N 125 Main St).
SITE_CITY	Site city	City in which the physical property resides (e.g., Chicago, Atlanta, Denver).
SITE_STATE	Site state	Two-letter state code where the physical property resides (e.g., CA, NV, WA).
SITE_ZIP	Site postal code	Postal code in which the physical property resides (e.g., 92675).
_X_COORD	Longitude	Longitude
_Y_COORD	Latitude	Latitude
COUNTY	County name	County name
CENSUS_TRACT	Census tract	Small, relatively permanent statistical subdivisions of a county or equivalent entity that are updated by local participants prior to each decennial census as part of the Census Bureau's Participant Statistical Areas Program
CENSUS_BLOCK_GROUP	Census block group	Block group: Geographical unit used by the United States Census Bureau that is between the census tract and the census block.
BLOCK_NUMBER	Block number	The census block of the subdivision or city in which the property is located.
OWNER_OCCUPIED	Owner occupied	Indicates if the property is occupied by the owner (Y/N).
USE_CODE_STD_LPS	Standardized land-use normalized code	Standardized land use code normalized across all counties. Indicates the use of a property. Refer to USE_CODE_STD_DESC_LPS field for the corresponding description.
USE_CODE_STD_DESC_LPS	Land-use description	Description of the USE_CODE_STD_LPS field
USE_CODE_STD_CTGR_LPS	Land-use standardized category code	Standardized land-use category code. Refer to USE_CODE_STD_CTGR_DESC_LPS field for the corresponding description.

Field Name	Field Alias	Description
USE_CODE_STD_CTGR_DESC_LPS	Land-use standardized CTGR description	Description of the USE_CODE_STD_CTGR_LPS field.
VAL_ASSD_LAND	Assessment value land	The assessed land value (before exemptions, if any) as provided by the county or local taxing/assessment authority.
VAL_ASSD_IMPRV	Assessment value improvement	The assessed improvement values (before exemptions, if any) as provided by the county or local taxing/assessment authority
VAL_ASSD	Assessment value	The total assessed value of both land and improvement values (before exemptions, if any) for the property as provided by the county or local taxing/assessment authority.
ASMT_YEAR	Assessment year	Year in which the property was assessed.
ZONING	Zoning	Actual city zoning that is unique to each incorporated area as reported to the county. Please note that it is not always current, nor reported.
LOT_SIZE_AREA_ORGN	Total square footage of the land	The total square footage of the land.
YR_BLT	Year built	Year the primary structure on the property was built.
BLDG_NUMBER	Number of buildings	Total number of buildings or structures on a single parcel as reported on the assessment roll.
BUILDING_SQFT	Building square foot	The building area of the primary structure on the property. If there are multiple residential units, then this is primarily the area of the largest residential structure. If the building is used in multiple ways (e.g., commercial plus residential), then the value is typically equal to the residential living area.
STORIES_NUMBER	Number of stories	Number of stories of the main structure on the property.
TOTAL_ROOMS	Total rooms	Total number of rooms reported on the assessment roll.
UNITS_NUMBER	Number of units	Number of units reported on the assessment roll. Primarily used for reporting of apartment buildings.
BEDROOMS	Bedrooms	Count of bedrooms (with closet). Residential only.
TOTAL_BATHS_CALCULATED	Total baths calculated	Number of full plus partial baths.
GARAGE_CARPORT_TYPE	Garage carport type	Code indicating type of garage or carport present (e.g., attached finished, enclosed carport, basement garage). Refer to the GARAGE_CODE_DESC field for the corresponding description.
PARKING_SPACES	Parking spaces	Total number of parking spaces or car capacity associated with the garage or parking area.
POOL_INDICATOR	Pool indicator	Code indicating the type of pool on the property (e.g., above ground, in ground, spa).
VAL_MARKET	Market value	Total market value as determined by the county or local taxing/assessment authority.
YR_MRKT_VAL	Market value year established	Year that market values were established.
BLDG_CLASS_DESC	Building classification code description	Description of the BLDG_CLASS field (see "Building Class" in the Code_Description tab).
STYLE_DESC	Building style description	Description of the STYLE_TYPE field.
CONSTRUCTION_CODE_DESC	Construction code description	Description of the Construction_Code field (see "Construction Type" in the Code_Description tab).

Field Name	Field Alias	Description
EXTERIOR_WALL_DESC	Exterior wall description	Description of the Exterior_Wall_Type field.
FOUNDATION_TYPE_DESC	Foundation type description	Description of the Foundation_Type field.
ROOF_COVER_DESC	Roof cover description	Description of the ROOF_COVER_TYPE field.
HEATING_DESC	Heating description	Description of the Heating_Type field.
AIR_CONDITIONING_TYPE_DESC	Air conditioning type description	Description of the air_conditioning field (see "Air Conditioning Type" in the Code_Description tab).
CAL_ACREAGE	Calculated acreage	Calculated acreage derived from the associated parcel geometry.
PRICE_PER_SQFT	Market price per square foot	Property price per square foot calculated by leveraging the latest market sale price and assessed square feet of the property.
LAND_PER_SQFT	Land value per square foot	Assessed land value per square foot.
LAND_SQFT	Land square foot	The size of the property, in square feet, derived from the assessment record when possible, otherwise calculated from associated parcel geometry.
CAL_SQFT	Calculated land square foot	Calculated square feet derived from the associated parcel geometry.
ASSOCIATE_PROPERTY_COUNT	Associated property count	Number of properties associated with a parcel.
TOPOGRAPHY_DESC	Topography description	Description of the TOPOGRAPHY field.
LOT_WIDTH	Lot width	The linear feet across the front of the lot; often the side of the property facing the street.
LOT_DEPTH	Lot depth	The linear feet between the front and back of the lot.
AVM_VALUE	Property value automated valuation model	Property value determined by an automated valuation model. Often based on comparable properties at a specific point in time.

Appendix E. Distributed Solar Results

In this appendix, we provide a summary of the solar photovoltaics (PV) results for selected scenarios from the analysis. We begin by summarizing the estimated technical potential values for the Baseline 2022, Baseline 2035, and Optimistic scenarios (Table E1). We then provide additional results separated for behind- and front-of-the-meter PV applications.

Table E1. Technical Potential for Behind-the-Meter and Front-of-the-Meter Applications for Distributed Solar Energy

Application	Technology	Technical Potential (gigawatts [GW])		
		Baseline 2022	Baseline 2035	Optimistic
Front of the Meter	Solar	419,659	441,160	445,062
Behind the Meter	Solar	2,816	2,816	3,064

E.1 Behind-the-Meter Applications

Solar applications are often more cost-effective than wind in behind-the-meter applications, evidenced by their higher threshold capital expenditures (CapEx). Of course, this generalization does not hold true in all cases and further site-specific comparisons could provide additional insight into the relative competitiveness of distributed wind and solar including highlights of locations where distributed wind and distributed solar have relative advantages.

In this context, Figure E1 shows the 80th percentile threshold CapEx value by state for behind-the-meter solar under the Baseline 2022 scenario. California and the Northeast states, specifically Massachusetts, Connecticut, and New Hampshire, have the highest threshold CapEx values for solar. One takeaway is that locations where retail electricity prices are higher are likely to be profitable for behind-the-meter applications. Figure E2 shows the county resolution for the states that have the highest threshold CapEx values. As shown in the figure, nearly all counties in California have a high threshold CapEx, confirming the attractiveness of this state for behind-the-meter solar applications.

Figure E1. Behind-the-meter solar threshold CapEx by state; Baseline 2022 scenario

Figure E2. States and counties with the highest threshold CapEx for behind-the-meter solar

E.2. Front-of-the-Meter Applications

Figure E3 shows the highest threshold CapEx values by state for front-of-the-meter solar for the Baseline 2022 scenario. States with a higher solar resource, namely Nevada, New Mexico, Arizona, and California, have the highest threshold CapEx values. Figure E4 shows the counties within these states and their comparative threshold CapEx. Sites that were evaluated in counties that are not colored were found to be unsuitable for front-of-the-meter solar applications and thus do not have any threshold CapEx value. A notable observation is that only a few counties within these states have a very high threshold CapEx, indicating limited land availability for front-of-the-meter solar energy development.

Figure E3. Front-of-the-meter solar threshold capital expenditures (CapEx) by state under the Baseline 2022 scenario

Figure E4. States and counties with the highest threshold CapEx for front-of-the-meter solar

Appendix F. Energy Equity Indices

F.1 Identifying Parcels in Disadvantaged Communities

In this study, we are interested in identifying how much technical potential exists in disadvantaged communities. To identify parcels in disadvantaged areas, we used the following data sets to identify disadvantaged census tracts and census block groups: Energy Justice (EJ) Indexes from the United States Environmental Protection Agency's (EPA's) EJ Screen (EPA 2020a) and Brownfield Sites (EPA 2020b) by census block group and the National Renewable Energy Laboratory's REPLICA data set (by census tract).

The following thresholds were assigned to identify disadvantaged block groups:

- Brownfield sites: any block group with at least one brownfield site.
- EJ Indexes (all the environmental indicators in Table F1 include the following demographic information: low-income population and minority population in their respective indexes).

Table F1. EJ Indexes

EJ Index	Threshold
National scale air toxics assessment air toxics cancer risk	75th percentile (or greater)
National scale air toxics assessment respiratory hazard	75th percentile (or greater)
National scale air toxics assessment diesel particulate matter (DPM)	75th percentile (or greater)
Particulate matter (PM2.5)	75th percentile (or greater)
Ozone	75th percentile (or greater)
Lead paint indicator	75th percentile (or greater)
Traffic proximity and volume	75th percentile (or greater)
Proximity to risk management plan sites	75th percentile (or greater)
Proximity to treatment storage and disposal facilities	75th percentile (or greater)
Proximity to national priorities list sites	75th percentile (or greater)
Wastewater discharge indicator	75th percentile (or greater)

The following thresholds and conditions were assigned to identify disadvantaged tracts:

- Tracts with low-income housing tax credit qualifiers
- Tracts with households with greater than the average US GINI index (0.390) OR tracts with a percent of the population of adults (25 years or older) with no high school education higher than the national average percent of adult population without a high school education
- Tracts with the percent of very low-income, single-family rented households is higher than the national average percent of very low-income, single-family rented households AND tracts with the percent of very low-income, single-family owned households is less than the national average percent of very low-income, single-family owned households
- Tracts with the percent of very low-income, multifamily rented households is higher than the national average percent of very low-income, multifamily rented households AND tracts with the percent of very low-income, multifamily-owned households is less than the national average percent of very low-income multi-family-owned households
- Tracts with the percent of low-income, single-family rented households is higher than the national average percent of low-income, single-family rented households AND tracts with the percent of low-income, single-family-owned households is less than the national average percent of low-income, single-family-owned households
- Tracts with the percent of low-income, multifamily rented households is higher than the national average percent of low-income, multifamily rented households AND tracts with the percent of low-income, multifamily-owned households is less than the national average percent of low-income, multifamily-owned households.

Using these parameters, we merged the disadvantaged block groups and tracts with the parcel data to identify disadvantaged parcels.

F.2 Solar Opportunities in Disadvantaged Communities

Here, we explore opportunities for distributed solar energy in disadvantaged communities using results from the Baseline 2022 scenario.

F.2.1 Front of the Meter

Disadvantaged communities represent 28% of all parcels where front-of-the-meter solar applications can be sited within the contiguous United States. Although front-of-the-meter distributed solar may not be applicable for many disadvantaged communities, our state-level results highlight some promising potential. The states with the highest economic potential in these disadvantaged communities include New Mexico, Nevada, California, Arizona, Virginia, and South Carolina. The specific areas within the states with the most promising opportunities in disadvantaged communities are highlighted in Figure F1.

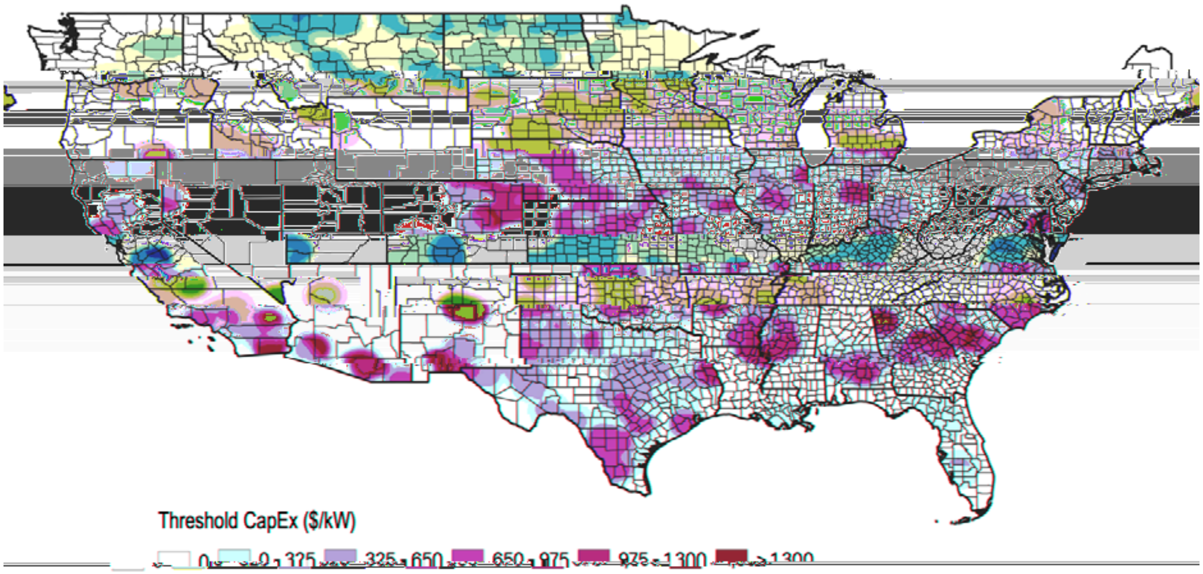


Figure F1. Threshold CapEx by state and county for front-of-the-meter solar in disadvantaged communities; Baseline 2022 scenario

F.2.2 Behind the Meter

At the national level, disadvantaged communities represent 48% of all parcels where behind-the-meter solar applications can be sited. By comparing threshold CapEx values among communities by state, we discovered that some states have more promising opportunities for disadvantaged communities than others. The states with the highest economic potential in these communities include California, Massachusetts, New Jersey, New Hampshire, Connecticut, and Maine. The specific areas within the states with the most promising opportunities in disadvantaged communities are highlighted in Figure F2. By 2035, these results are expected to vary based on changes in policy and the potentially projected value of distributed energy resources.

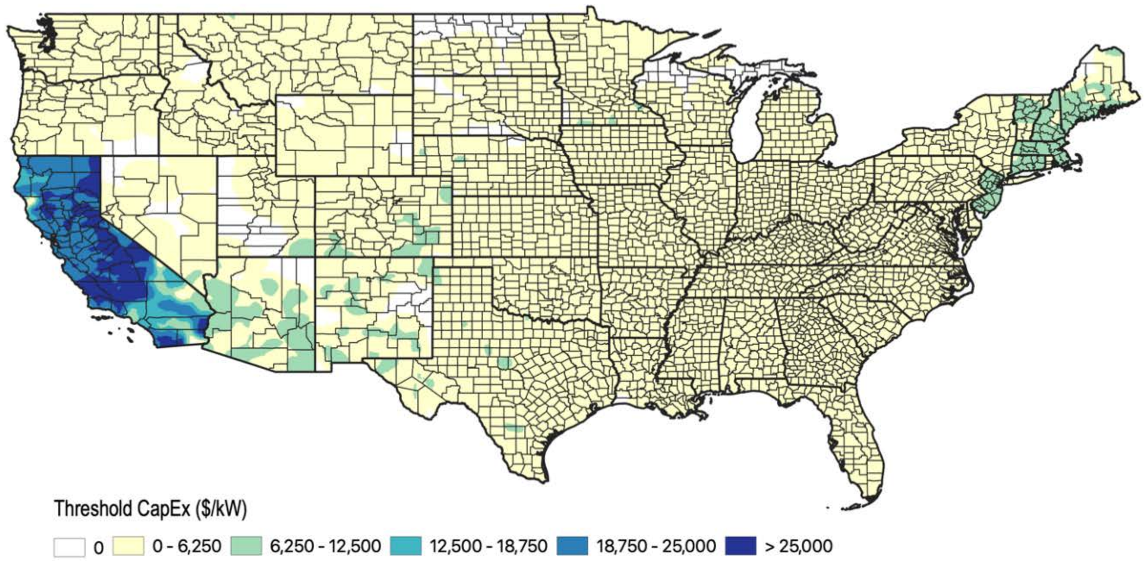


Figure F2. Threshold CapEx by state and county for behind-the-meter solar in disadvantaged communities; Baseline 2022 scenario