Preziuso *et al.*
*Energy, Sustainability and Society* (2022) 12:31
https://doi.org/10.1186/s13705-022-00357-1

Energy, Sustainability
and Society

RESEARCH

Open Access

# Categorizing distributed wind energy installations in the United States to inform research and stakeholder priorities

Danielle Preziuso[1*], Alice Orrell[1] and Eric Lantz[2]

## Abstract

**Background:** Distributed wind energy adoption in the United States can contribute to the diverse portfolio of energy technologies needed to achieve ambitious decarbonization goals. However, with limited deployment to date, the current distributed wind market must be better understood; these efforts will support the range of stakeholders who will drive successful deployment. This article first distinguishes three categories of distributed wind from existing literature: (1) behind the meter, (2) intended for explicit local load, and (3) physically distributed. A novel methodology to classify individual wind installations into each of these categories is then presented and applied to two data sets of wind installations in the United States to categorize and illuminate distinct segments in the distributed wind market.

**Results:** Physically distributed installations, constituted by small to moderately sized projects serving local loads on distribution systems solely because of their proximity to them, account for the highest amount of capacity but the lowest number of installations out of the three categories. The inverse is true for behind-the-meter installations, which are used to serve on-site loads. Installations intended for explicit local load, which are interconnected on the utility side of the distribution system and intentionally built to provide energy to loads on the same distribution system, rank in the middle for both installed capacity and number of installations.

**Conclusions:** Distributed wind energy deployment in the United States is geographically widespread, but the extent to which a single category is developed in each state varies. Policies, wind resources, and broad energy technology trends contribute to these deployment patterns. By identifying the extent to which each category of installations exists, decision-makers are empowered with data necessary to tailor research and development programs and address stakeholder priorities through policy and other means, ultimately supporting future deployment.

**Keywords:** Distributed wind, Wind energy, Market categorization

## Background

As societies aim to decrease carbon emissions from the energy sector and enhance energy access [1, 2], the world is witnessing an increase in distributed energy resource adoption.[1] In the United States, the predominant distributed energy resource is rooftop solar photovoltaics (PV) [3]. While non-distributed, utility-scale wind energy technologies have seen significant deployment and declining costs in recent years [4], the same trends have not been observed for distributed wind. Installation costs and siting challenges [5–8] persist as some of the reasons distributed wind has not experienced parallel growth with distributed solar PV. Ambitious decarbonization

*Correspondence: danielle.preziuso@pnnl.gov

[1] Pacific Northwest National Laboratory, 902 Battelle Boulevard, Richland, WA, USA
Full list of author information is available at the end of the article

---

[1] *Decentralized energy resources* is an alternative name for *distributed energy resources*.

and energy access goals may, however, require a broader array of renewable energy solutions. Energy generation facilities that are tailored to better serve end-users and local communities with accompanying smart technologies, hybridization, and energy storage are likely to play a large role in the array of future solutions. These tailored generation facilities are particularly relevant within the context of emerging concepts, such as energysheds and smart local energy systems [9, 10].

The general characteristics of distributed generation and distributed energy resources, including distributed wind, are typically understood and agreed upon, but specific definitions vary [11–14]. The variability in definitions leaves gaps and vagueness that erode important nuances affecting decision outcomes. Per existing literature, distributed wind energy installations are classically identified by their relatively small installed capacity, their supply of energy to loads on distribution systems or off-grid applications, and their proximity to where their energy is consumed [6, 15–17]. These identified characteristics give way to three categories of distributed wind installations, which we distinguish as (1) behind the meter, (2) intended for explicit local load, and (3) physically distributed.

Behind-the-meter installations are used to serve on-site loads interconnected to a distribution system behind a customer's meter and are typically sized to meet that particular load [6, 16, 17]. Behind-the-meter installations are often enrolled in net metering programs that compensate the owner for the excess electricity that is exported to the electric grid [18]. In comparison, distributed wind installations intended for explicit local load include projects that are interconnected on the utility side of the distribution system as opposed to the customer side of the meter. This type of project can also be referred to as a front-of-the-meter installation. These projects are specifically built to provide energy to a nearby load or loads interconnected to the same distribution system. Finally, physically distributed installations are those that naturally meet the defining characteristics of distributed wind through their relatively small size and proximity to loads; however, these facilities have not been developed behind the meter or with the explicit intention to serve a local load.

For distributed wind to play a larger role in a more diverse distributed energy future, the existing distributed wind market must first be understood and appropriately categorized as a baseline. This baseline assessment is critical to inform research and development efforts needed for the range of stakeholders who will drive successful deployment. Research and development priorities range from technical assessments of the wind resource [8] and optimizing wind turbine model designs [19] to conducting direct market and policy analysis [16]. Wind turbine manufacturers and project developers need to understand where their technologies and business models fit in the market, respectively. They also need to know what the future outlook of the market is, and what policies and incentives are available for use [16]. Moreover, decision-makers and policymakers, particularly at the state level, can review the categorizations to understand the implications their policies have on distributed wind deployment and whether or not any policy changes are needed to achieve their clean energy goals.

Although agencies and organizations that fund distributed wind deployment are required to define distributed wind to administer their programs [6, 11–15], wind installations are not often recorded and tracked in the United States in a way that aligns with the defining criteria of distributed wind. This makes it challenging to determine if a given wind installation is a distributed energy resource. For example, some public data organizations only track distributed resource capacity in aggregate at the utility level [20] or the distribution voltage of individual projects [21], but these characteristics are insufficient to identify the different categories of the market.

The range of applications in which distributed wind energy technologies can be deployed, the number and size of wind turbines in an installation, and the ways in which distributed wind installations can be interconnected to the electric grid make characterizing and categorizing the distributed wind market difficult. This challenge is further compounded by the absence of a distinct definition for distributed energy resources. The complexity of the task along with the dearth of clear definitions, boundaries, and categories works against the sophisticated understanding that would help inform policies and research and development to enable new deployment. Previous efforts to characterize the wind energy market have analyzed turbine and project capacity, turbine size, and location of the project by state [4, 22]. Distributed wind market characterizations have only focused on behind-the-meter and front-of-the-meter distributed wind installations [23]. No previous efforts have provided a step-by-step method to characterize the entire distributed wind market into behind-the-meter, intended for explicit local load, and physically distributed categories.

The distributed wind identification methodology presented in this paper addresses this gap. It provides a singular, methodical way to categorize existing distributed wind installations to bridge the gap between broadly understood definitions that might lack important specificity and helpful information to support the full realm of research, development, and stakeholder priorities in

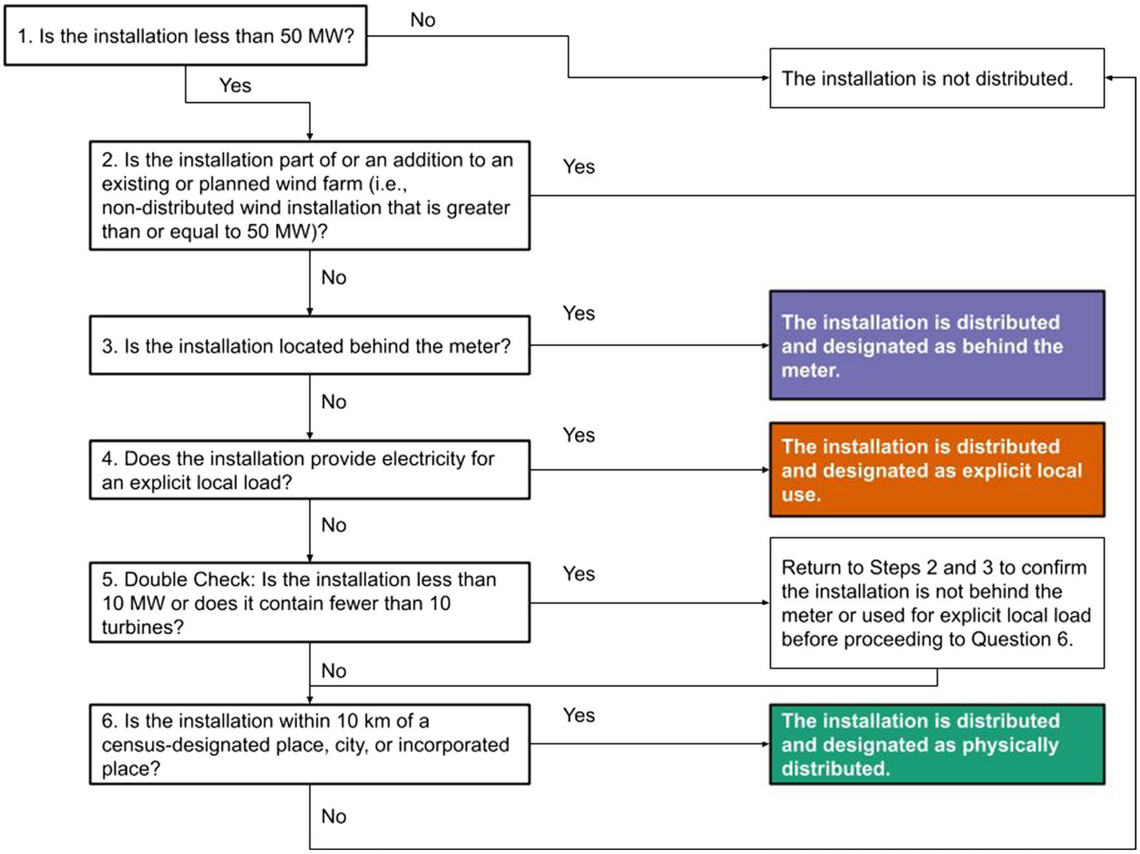

**Fig. 1** Distributed wind identification methodology flow diagram

the distributed wind community. The methodology uses publicly available data to categorize individual distributed wind installations as behind the meter, intended for explicit local load, or physically distributed. By understanding the extent to which each of these categories of distributed wind has been deployed in the United States, research and development efforts can be tailored accordingly, policies can be evaluated and adjusted as needed, and industry stakeholders can shape their business strategies based on a defined market.

In this paper, the distributed wind identification methodology is demonstrated by applying it to two existing data sets of wind installations in the United States: the Pacific Northwest National Laboratory (PNNL) Project Data Set [24] and the United States Wind Turbine Database (USWTDB) [25]. The combination of these two data sets provides the most comprehensive, publicly available list of installation-level information for wind energy projects in the United States. A breakdown of the U.S. distributed wind market is then presented by installed capacity and number of installations in each of the defined distributed wind categories. States with significant deployment are highlighted to enable a discussion of potential driving factors for deployment trends before the practical benefits of the methodology are established and avenues for future work are explored.

## Methods

To develop a standardized methodology for categorizing different segments of the distributed wind market in the United States, it is necessary for installations to be considered under the three defining characteristics of distributed wind—(1) relatively small installed capacity, (2) supply energy to loads on the same distribution systems or in off-grid applications, and (3) close proximity to where the energy is consumed [6, 15–17]. An installation is assigned to a category of distributed wind based on how it fulfills those defining characteristics. The distributed wind identification methodology can be thought of as a step process (see Fig. 1) that asks a series of questions to determine if an installation is behind the meter, intended for explicit local load, or physically distributed. If an installation does not meet the requirements of the methodology, it is not considered a distributed wind installation. The order of the questions in the distributed wind identification methodology is critical, unless otherwise stated, because the categorizations are established based on the cumulative information known about each installation. The methodology is designed to be applied to a data set of individual wind energy installations, where each installation (with one or many wind turbines) is considered independently.

### Application

The distributed wind identification methodology was applied to installations in the PNNL Project Data Set [24] and the USWTDB [25]. The USWTDB tracks all land-based and offshore wind turbines with a focus on turbines greater than 100 kW in capacity. Turbines installed from 2001 through 2021 were considered in this application of the methodology. In comparison, the PNNL Project Data Set is dominated by installations smaller than what is contained in the USWTDB, focusing on distributed wind installations dating from 2003 up through 2021. While PNNL's Project Data Set tracks distributed wind installations, the data set was compiled based on general characteristics of distributed wind rather than with a step-by-step, defined methodology. Applying the distributed wind identification methodology to the installations in the PNNL Project Data Set categorizes those installations and verifies they meet the defining characteristics of distributed wind. In combination, the USWTDB and PNNL Project Data Set have turbines ranging in size from 160 W to 6 MW.

Some of the same projects are included in both the USWTDB and PNNL's Project Data Set. The USWTDB tracks individual wind turbines, whereas the PNNL Project Data Set aggregates turbines by project. The turbines in the USWTDB were aggregated to the project level before the installed capacity, number of turbines, and names of each project in the two data sets were compared to identify duplicate entries. Duplicate entries were then manually resolved before the distributed wind identification methodology was applied to the reconciled data set.

The individual steps of the distributed wind identification methodology (per Fig. 1) that were answered for each of the installations in the combined PNNL–USWTDB project data set are detailed in the subsections that follow. Each step includes guidelines on how to answer the question, drawing upon industry data and best available practices. Every installation is assigned to a category of distributed wind or otherwise identified as a non-distributed installation.

### Is the installation less than 50 MW?

Distributed wind installations are smaller in size than non-distributed, utility-scale wind farms. The accepted threshold for what constitutes relative smallness varies in practice. The system size needs to not simply be small, but to be small relative to centralized power plants. Two sources that define small installation sizes were referenced for this characteristic: the Federal Energy Regulatory Commission (FERC) and the Public Utility Regulatory Policies Act [26, 27].

FERC regulates the interstate transmission of electricity, natural gas, and oil in the United States and defines small generators for the purpose of interconnection regulations. In Order No. 842, FERC defines small generators as those up through 20 MW in size [27]. In comparison, the Public Utility Regulatory Policies Act considers small power generation facilities to be no greater than 80 MW in size [26]. Intended to support the use of renewable energy technologies and cogeneration after the energy crisis in the 1970s, the Public Utility Regulatory Policies Act established requirements for utilities to purchase electricity from small production plants and cogeneration facilities [28].

A cutoff threshold of 50 MW was adopted in this study as a conservative compromise between those two sources and is implemented as the first question in the methodology. This question immediately removes installations that do not fit the size requirement for distributed wind without creating a narrow view on relative smallness. If an installation is 50 MW or greater, it is not considered distributed wind and the step-by-step process ends for the given installation. If an installation is less than 50 MW, the installation moves to the second question in the methodology.

### Is the installation part of or an addition to an existing or planned wind farm (i.e., non-distributed wind installation that is greater than or equal to 50 MW)?

In addition to setting a size threshold for distributed wind energy projects, it is critical to remove installations that might appear to fall below the 50-MW threshold but are actually expansions of larger facilities. Question two in the methodology addresses this possibility and speaks to how large wind energy installations can be developed in phases of varying size. This question eliminates installations that, when combined with other development phases, exceed the original size threshold of 50 MW. This question can most often be answered by reviewing past records on the installation's other phases as well as news articles. Sometimes the installation names (e.g., Windy Point Phase 3) and locations can also indicate this type of occurrence. Wind turbines that are part of, or are an addition to, an existing or planned installation that is greater than or at the 50-MW threshold are removed from the assessment at this step. While this question is listed second in the methodology, in practice, it could be switched with question three and produce the same results.

### Is the installation located behind the meter?

Net metered installations, which make up a large portion of behind-the-meter installations, are well-tracked throughout the United States [20], but not all behind-the-meter installations are enrolled in net metering programs. To identify whether an installation is located behind the meter, installer reports, news stories, and project names can provide the needed information. Most installations located behind the meter are particularly small in size, much less than 50 MW. Thus, if the answer to the third question in the methodology is "yes" (i.e., the installation is behind the meter), the installation readily meets the other two characteristics of distributed wind (i.e., supply energy to loads on distribution systems and close proximity to where the energy is consumed). If an installation is identified as behind the meter, it is assigned to the behind the meter distributed wind category. If the response to the third question is "no", the installation moves to question four in the methodology.

### Does the installation provide electricity to an explicit local load?

Compared to behind-the-meter installations, it is more challenging to identify installations that are intended for explicit local loads, because the objective of the project's implementation must be addressed, which could be a qualitative matter. While the term local is subjective, a local load is considered one that is on the same distribution system as the wind installation within the context of the distributed wind identification methodology. News stories and installer reports often include information about the intent of the project, but direct consultation with owners and developers can also provide insight into this aspect of an installation's development. Wind projects built to serve specific communities tend to be particularly well-documented in the media. Two 10.5-MW wind projects interconnected to the Iowa Lakes Electric Cooperative distribution system are considered example projects for other electric cooperatives to study. These installations provide electricity to ethanol plants on the cooperative's distribution system while keeping costs down for all members [29].

By reaching question four and being categorized as intended for explicit local load, an installation has met the defining requirements of distributed wind; it is under the size threshold and provides electricity to proximal loads on a distribution system. If an installation cannot be identified as providing energy for an explicit local load, the installation moves to question five in the methodology.

### Double Check: Is the installation less than 10 MW or does it contain fewer than 10 turbines?

Before evaluating the proximity to load to determine if a project is physically distributed, the fifth question in the methodology is a double-check for installations that are 10 MW or less or contain fewer than 10 wind turbines. While a threshold of 50 MW was used to eliminate large, centralized wind farms, smaller installations will likely be located behind a customer meter or developed explicitly for a local load. This warrants additional effort to verify that small installations, with respect to installed capacity or number of turbines, have not been overlooked in either of these categories. If the small installation can still not be categorized as either behind the meter or intended for explicit local load after additional investigation, it proceeds to the sixth question.

### Is the installation within 10 km of a census-designated place, city, or incorporated place?

Interconnection voltage levels, on their own, are not a sufficient measurement for categorizing distributed wind installations. The distribution voltage does not directly correlate to project size or proximity to load. Many wind installations in the United States use distribution-level interconnections to reach larger transmission lines to distribute energy at the bulk level rather than to service local loads [30, 31].

In addition, once electrons enter the electric grid, it is not possible to track, where they end up or what loads they serve, which can make defining proximity to load challenging. Given these constraints and the more readily available information about turbine locations, a geographic information system assessment is employed to assess physically distributed projects. This criterion is evaluated in the sixth question of the methodology: Is the installation within 10 km of a census-designated place, city, or incorporated place? Census-designated places, cities, and incorporated places are used as a proxy for load. A threshold of 10 km was selected after an analysis of wind turbine locations in the USWTDB [25] showed that 98% of turbines are within 30 km of a census-designated place, city, or incorporated place. In comparison, only 55% were within 10 km of one of those locations and 17% were within 5 km. Population size was initially considered in this process but ultimately not included in the distributed wind identification methodology because the size of the installation relative to load is not addressed within this work.

Thus, to answer the sixth question, an overlay analysis is performed in ArcGIS between turbine locations and census-designated places, cities, and incorporated places as identified in the U.S. Census Bureau's 2012–2016 American Community Survey 5-Year Estimates [32].

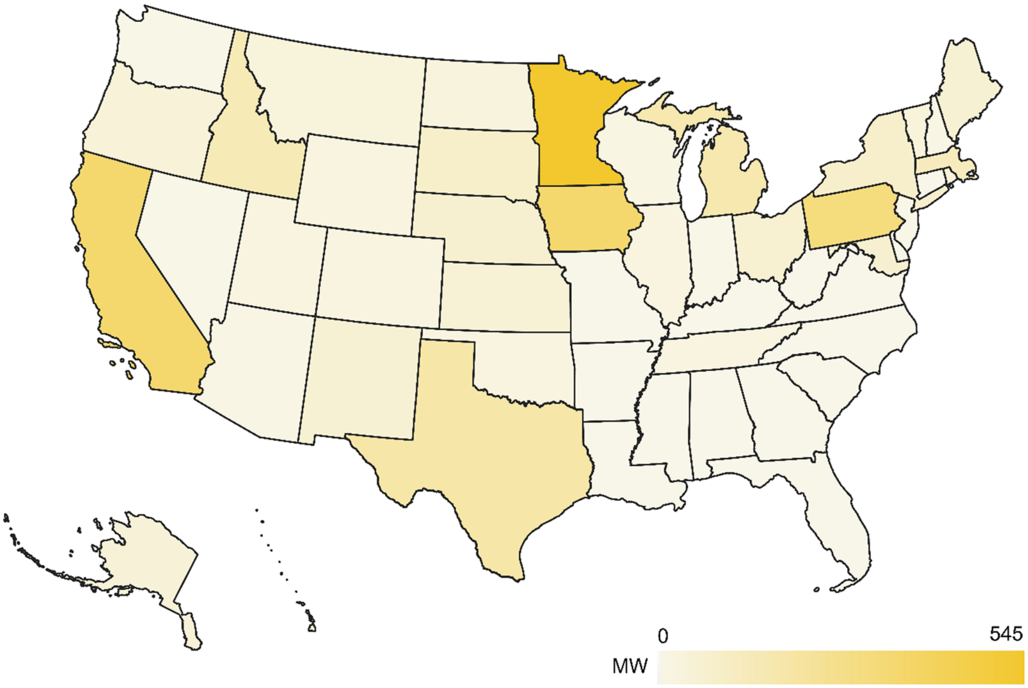

**Fig. 2** Cumulative installed distributed wind capacity in the United States from 2001 to 2021

While the two previous categories of distributed wind use qualitative information for categorization, the final category relies on knowing the location of the turbines relative to proxy loads. This final category captures distributed wind installations that were not developed with the intention of serving as a distributed energy resource. If an installation reaches this question in the methodology and is within 10 km of a census-designated place, city, or incorporated place, it is categorized as physically distributed. Physically distributed installations are under the 50 MW size limit, have met the proximity to load requirement through the geographic information system analysis, and are likely provide electricity to loads on nearby distribution networks because of their proximity to a city and the physics of electron flow. If an installation does not meet this final requirement in the methodology, it is not counted as distributed, and the process ends for the given installation.

## Results

Of the installations in the reconciled data set created from the USWTDB and PNNL's Project Data Set, the methodology indicates there are approximately 3326 MW of distributed wind installed in the United States from 2461 installations. For the 2461 installations identified, the state in which they were located was known for all but three of the installations. The installed distributed wind capacity is spread across all 50 states, as shown in Fig. 2. Minnesota, Iowa, California, Pennsylvania, Texas, and Michigan have seen the highest rates of distributed wind energy deployment on a capacity basis. Of the 3326 MW installed, 71% comes from physically distributed installations, with explicit local load installations contributing to slightly more than half of the remaining 29%. Behind-the-meter installations contribute the least amount of capacity to the distributed wind energy market in the United States.

A breakdown of the categories of distributed wind in each of the six states that have seen the highest deployment is shown in Fig. 3; the full categorization by state is provided in Table 1. Minnesota has installed the greatest amount (406 MW) of distributed wind in physically distributed applications, followed by Pennsylvania and California. Iowa has seen the most capacity deployed in installations intended for explicit local load (168 MW), followed by Minnesota (108 MW). California has seen the most capacity (69 MW) deployed in behind-the-meter applications.

When the market is considered by number of installations rather than installed capacity, the opposite trend is seen. Approximately 87% of project installations are located behind the meter, with explicit local load making up a modest majority of the remining 13% of installations. The distribution of cumulative distributed wind deployment by number of installations is shown in Fig. 4, and Table 2 lists the number of projects in each state by

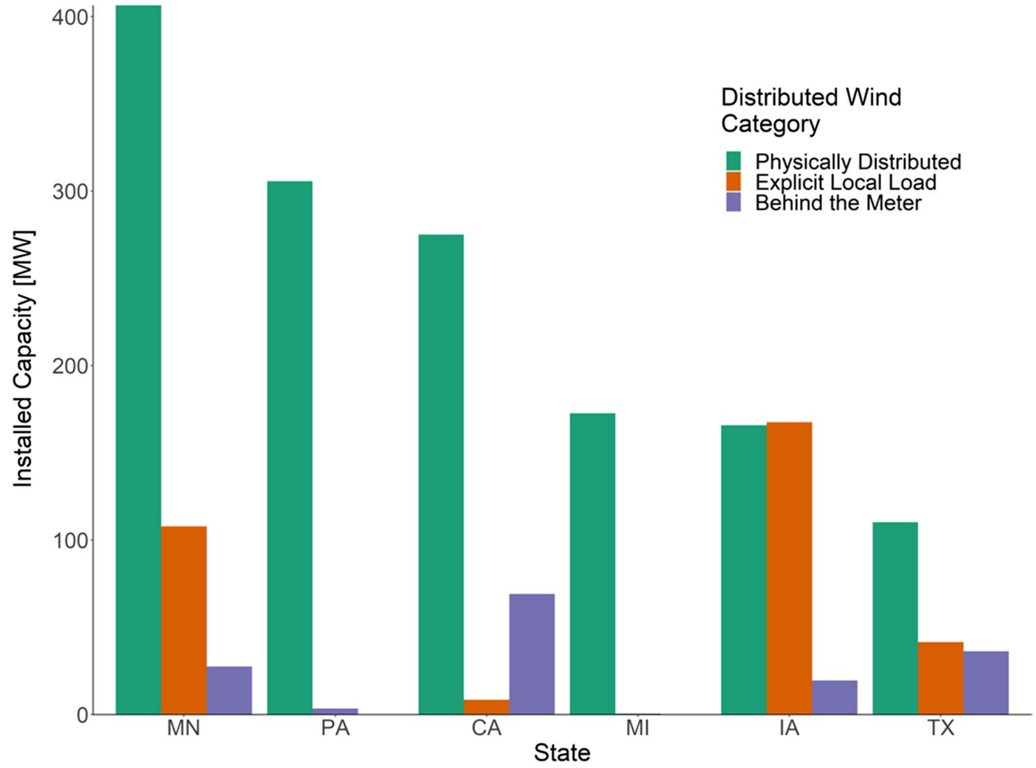

**Fig. 3** Distributed wind categories for the six states with the highest cumulative capacity of installed distributed wind

distributed wind category. Iowa, New York, and Minnesota have seen the greatest number of distributed wind installations, with none of the remaining states reaching even 50% of the number of installations seen within any of those top three states.

The observed trends in installed capacity versus number of installations in each category is not unexpected. Installations developed behind the meter are generally much smaller in size than those developed for explicit local load and physically distributed installations, as shown in Table 3. The installations that were categorized as behind the meter in this application of the methodology were largely built to serve the loads from individual buildings, small farms, and schools, whereas installations developed for explicit local load were often at the community level, providing capacity to a utility's service area. Physically distributed installations were void of a relationship to a specific load.

## Discussion

Categories of distributed wind installations and capacity levels vary across the United States. A total of 3326 MW was identified using the distributed wind identification methodology, with 406 MW being behind the meter, 550 MW intended for explicit local load, and 2370 MW being physically distributed. The categorization of these distributed wind projects across the country, through a replicable methodology, can inform research and development efforts as well as address the range of stakeholder priorities that would allow for increased deployment. State policy-makers, wind turbine manufacturers, and project developers are key stakeholders who could benefit from this categorization. The significance of this categorization for these stakeholders can be illustrated through the states that have seen high amounts of installed capacity and high numbers of installations.

California has the largest installed capacity of behind-the-meter installations (69 MW). While most behind-the-meter installations are less than 40 kW in size, larger behind-the-meter projects that serve energy-intensive industrial loads were also identified. For example, one 24-MW project for a cement plant in Tehachapi [33] accounts for 35% of California's behind-the-meter capacity. California has had several programs and incentives supporting the adoption of small and distributed energy resources, including the Emerging Renewable Program (ended in 2012) and the Self-Generation Incentive Program (ended in January 2021) [34, 35]. Both programs provided cash incentives to distributed energy resource owners. The Emerging Renewable Program required

**Table 1** Installed capacity in each distributed wind category by state[2]

| State | Behind the meter (kW) | Explicit local load (kW) | Physically distributed (kW) | Total (kW) |
|---|---|---|---|---|
| AK | 4002 | 23,225 | 24,600 | 51,827 |
| AL | 2 | – | – | 2 |
| AR | 104 | – | – | 104 |
| AZ | 1083 | – | 10,000 | 11,083 |
| CA | 69,132 | 8482 | 275,010 | 352,624 |
| CO | 11,027 | 16,400 | – | 27,427 |
| CT | 115 | 5000 | – | 5115 |
| DE | 2002 | – | – | 2002 |
| FL | 186 | – | – | 186 |
| GA | 7 | – | – | 7 |
| HI | 3586 | – | 68,160 | 71,746 |
| IA | 19,573 | 167,560 | 165,800 | 352,933 |
| ID | 31 | – | 143,600 | 143,631 |
| IL | 9186 | 12,950 | – | 22,136 |
| IN | 7350 | 1850 | – | 9200 |
| KS | 10,347 | – | 48,300 | 58,647 |
| KY | 80 | – | – | 80 |
| LA | 60 | – | – | 60 |
| MA | 54,787 | 27,400 | 45,150 | 127,337 |
| MD | 1150 | – | 70,000 | 71,150 |
| ME | 929 | 4500 | 55,800 | 61,229 |
| MI | 532 | – | 172,600 | 173,132 |
| MN | 27,501 | 107,780 | 406,330 | 541,611 |
| MO | 93 | 5000 | – | 5093 |
| MS | 2 | – | – | 2 |
| MT | 1681 | 2000 | 38,000 | 41,681 |
| NC | 101 | – | – | 101 |
| ND | 3355 | – | 31,380 | 34,735 |
| NE | 1825 | 33,850 | 36,000 | 71,675 |
| NH | 163 | – | 14,250 | 14,413 |
| NJ | 9098 | – | – | 9098 |
| NM | 1500 | 34,750 | 27,300 | 63,550 |
| NV | 8955 | – | – | 8955 |
| NY | 12,506 | 100 | 71,000 | 83,606 |
| OH | 57,969 | 7200 | – | 65,169 |
| OK | 1054 | – | 21,720 | 22,774 |
| OR | 357 | 225 | 46,500 | 47,082 |
| PA | 3414 | – | 305,600 | 309,014 |
| RI | 19,310 | 24,275 | – | 43,585 |
| SC | 11 | – | – | 11 |
| SD | 1783 | 20 | 85,900 | 87,703 |
| TN | 7 | 2 | 27,000 | 27,009 |
| TX | 36,263 | 41,600 | 110,240 | 188,103 |
| UT | 3975 | – | 18,900 | 22,875 |
| VA | 397 | – | – | 397 |
| VT | 954 | 10,225 | 30,000 | 41,179 |
| WA | 350 | 10,250 | – | 10,600 |
| WI | 14,711 | 5100 | – | 19,811 |
| WV | 20 | – | – | 20 |
| WY | 3826 | – | 20,700 | 24,526 |
| Total | 406,449 | 549,744 | 2,369,840 | 3,326,033 |

[2] Individual capacity numbers for each state have been rounded to the whole number in tables. Totals reflect the summation before those values have been rounded

wind turbines to be permanently interconnected to the distribution grid and serve customer loads, helping motivate the installations of wind technologies behind the meter. Similarly, the Self-Generation Incentive Program targeted distributed energy resources located behind the customer meter explicitly. These two programs could serve as models to other states interested in sparking growth of the behind-the-meter sector or indicate to wind turbine installers and manufacturers that states considering these types of policies are future opportunities for behind-the-meter development.

New York's high number of installations, but relatively low installed capacity value, is driven by the large number of behind-the-meter small wind installations (where small wind is defined as turbines up through 100 kW in capacity [36]) for small farm and residential customers in the state. The New York State Energy Research and Development Authority's Small Wind Turbine Incentive Program ran from 2009 through 2019. The program provided funding for over 300 turbine unit installations totaling more than 8 MW of deployed distributed wind capacity [23]. Other states interested in supporting behind-the-meter small wind could model their programs after New York's.

In comparison, Iowa has significant capacity from explicit local load installations (168 MW). Strong wind resources, institutionalized support for distributed wind and other renewables via its incentive programs—such as its state production tax credit—and simple permitting processes in rural areas [37] enable a strong market in Iowa for projects that serve explicit local loads. Wind project owners are only eligible for the state production tax credit if they sell the electricity to a third party. This is an incentive for distributed wind projects to interconnect on the utility side of the distribution system and serve explicit local loads. Policy-makers that have similar strong wind resources in their state may consider replicating the permitting processes that Iowa has implemented or introducing a similar tax credit to support the development of front-of-the meter installations.

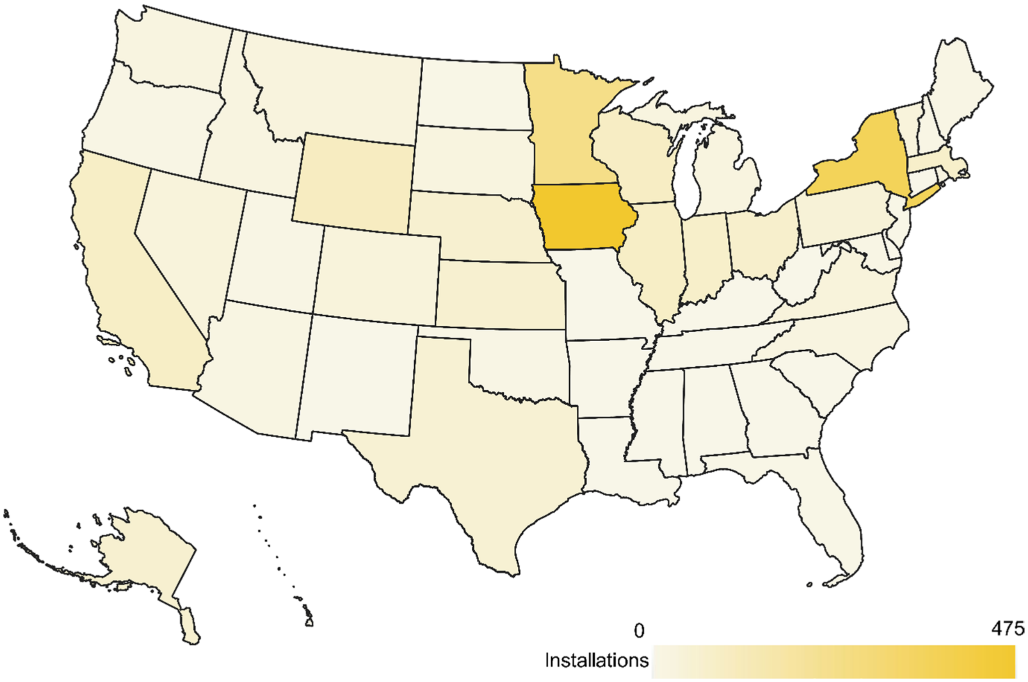

**Fig. 4** Number of distributed wind installations in each state from 2001 to 2021

Finally, the largest deployed capacity for physically distributed wind installations is in Minnesota (406 MW). In 2020, Minnesota saw nearly 30% of its in-state electricity generation come from renewables, with a large share of that from wind energy specifically [38]. It ranks among the top 10 states for its amount of wind-generated electricity [38] as well as total installed wind energy capacity, including non-distributed installations. Minnesota's high capacity of physically distributed wind projects is at least partially attributable to its overall high installed wind capacity. However, the relationship between physically distributed installations and overall wind energy installations is varied.

Table 4 lists the total installed wind capacity in each state based on the projects reported in both the USWTDB and PNNL's Project Data Set. While many states that have high amounts of physically distributed capacity also have significant capacity from non-distributed installations, there is not a direct correlation between the two. For example, Illinois and Colorado rank fifth and seventh in total installed wind capacity, respectively, but neither state has any physically distributed projects. Furthermore, the percentage of total wind capacity that qualifies as physically distributed in states where it is present ranged from less than 1% (Texas) to more than 93% (Tennessee). The average share of state-level total wind capacity that is physically distributed was 13%, while the median was 5%. Given this observed variability and skew in the data, drivers of high volumes of physically distributed capacity are presumably a function of multiple variables. Population density, topography, property parcel sizes and distributions, utility service territory characteristics, and other attributes of local wholesale power markets are likely among the drivers influencing the adoption of physically distributed wind installations.

Review of these distributed wind category distinctions can advise state policy-makers on how effective policies and programs have been in creating different distributed wind markets and in meeting clean energy goals. It can help them understand which size turbines are installed for what purpose, how many turbines are often seen in those applications, and how and where they are interconnected. It can also open opportunities to investigate other variables that have contributed to distributed wind deployment, such as the wind resource itself. Given the limited deployment of distributed wind technologies in the United States when compared to other renewable energy technologies such as distributed solar PV—which saw 4500 MW of capacity installed from systems under 1 MW in size during 2020 alone [39]—understanding where distributed wind has been successful is critical for supporting future deployment. It can also help identify why there are deployment differences across the states so that one may learn from another.

**Table 2** Number of installations in each distributed wind category by state

| State | Behind the meter | Explicit local load | Physically distributed | Total |
|---|---|---|---|---|
| AK | 32 | 31 | 1 | 64 |
| AL | 1 | – | – | 1 |
| AR | 2 | – | – | 2 |
| AZ | 16 | – | 1 | 17 |
| CA | 74 | 3 | 9 | 86 |
| CO | 31 | 4 | – | 35 |
| CT | 2 | 1 | – | 3 |
| DE | 2 | – | – | 2 |
| FL | 8 | – | – | 8 |
| GA | 3 | – | – | 3 |
| HI | 10 | – | 3 | 13 |
| IA | 419 | 48 | 6 | 473 |
| ID | 14 | – | 8 | 22 |
| IL | 81 | 7 | – | 88 |
| IN | 77 | 2 | – | 79 |
| KS | 65 | – | 1 | 66 |
| KY | 3 | – | – | 3 |
| LA | 1 | – | – | 1 |
| MA | 65 | 11 | 3 | 79 |
| MD | 9 | – | 2 | 11 |
| ME | 8 | 1 | 2 | 11 |
| MI | 23 | – | 6 | 29 |
| MN | 167 | 53 | 22 | 242 |
| MO | 4 | 1 | – | 5 |
| MS | 2 | – | – | 2 |
| MT | 25 | 1 | 4 | 30 |
| NC | 23 | – | – | 23 |
| ND | 8 | – | 2 | 10 |
| NE | 55 | 9 | 1 | 65 |
| NH | 13 | – | 1 | 14 |
| NJ | 9 | – | – | 9 |
| NM | 1 | 3 | 1 | 5 |
| NV | 36 | – | – | 36 |
| NY | 352 | 1 | 4 | 357 |
| OH | 72 | 2 | – | 74 |
| OK | 11 | – | 2 | 13 |
| OR | 10 | 1 | 4 | 15 |
| PA | 38 | – | 9 | 47 |
| RI | 13 | 9 | – | 22 |
| SC | 4 | – | – | 4 |
| SD | 24 | 1 | 4 | 29 |
| TN | 3 | 1 | 1 | 5 |
| TX | 39 | 7 | 9 | 55 |
| UT | 11 | – | 1 | 12 |
| VA | 37 | – | – | 37 |
| VT | 33 | 4 | 1 | 38 |
| WA | 19 | 2 | – | 21 |
| WI | 90 | 2 | – | 92 |
| WV | 2 | – | – | 2 |
| WY | 99 | – | 2 | 101 |
| Total | 2146 | 205 | 110 | 2461 |

This categorization can also help wind turbine manufacturers and project developers understand, where their companies fit within the different market categories and which policies and incentives would be applicable to their business models. For example, some project developers' business models are to build, own, and operate a wind turbine and sell the electricity to a single customer through a power purchase agreement. The wind turbine can either be behind the meter or interconnected on the utility side of the distribution system. The project developer could pick which states to operate in based on which interconnection type the state's policies and incentives favor (e.g., Iowa but perhaps not Michigan). A wind turbine manufacturer seeking investor capital to fund a new turbine model, in comparison, could assess the market to show potential investors target markets for their technology and the extent to which they prevail across the country.

There are several limitations within this study and the distributed wind identification methodology, however; some of these limitations create future research opportunities. While the methodology relies on publicly available information, such as news reports and the location of wind turbines, institutions that collect data on distributed energy resources may not track installation-specific details. For this reason, off-grid distributed wind installations are not captured through the methodology and subsequent analysis, since they are not well-documented throughout the country. In addition, several organizations, such as the U.S. Energy Information Administration, only publish aggregated information and limited project-level details about distributed energy resources [20, 21]. These data are in formats that do not fit into the methodology, because collecting highly detail information is not within their objectives. Granular information about wind installations can be time-consuming to obtain. In addition, much of the information about distributed wind energy deployment is collected by state agencies, turbine manufacturers, project developers, and utilities [16]. Some of these entities are better equipped than others to track this information or have distinct motivations for collecting different data points, potentially creating discrepancies in the quality and quantity of detail across the country. The methodology is only as successful as the data set to which it is applied.

**Table 3** Installation capacity statistics by distributed wind category. All capacity values are in kW

| | Behind the meter (kW) | Explicit local load (kW) | Physically distributed (kW) |
|---|---|---|---|
| Minimum | 0.16 | 1.9 | 1500 |
| First quartile | 2.6 | 750 | 10,125 |
| Median | 10 | 1600 | 20,000 |
| Third quartile | 39.4 | 3375 | 30,000 |
| Maximum | 24,000 | 30,000 | 49,500 |

Furthermore, because many qualitative data points are used to determine if installations are behind the meter or used for explicit local load, a large influx in installations, or even an increased cutoff threshold for question two in the methodology, would exponentially increase the amount of work to make those categorizations using the presented methodology. The methodology limits this labor to two individual steps for identifying installations that are behind the meter and intended for explicit local load, but overall, this would still prove time-consuming. Ways to incorporate different data sets and standardize and streamline the process further are potential areas of future work. Finally, closeness to load was determined through a proxy value with census-designated places for physically distributed installations. Future work evaluating the size of loads relative to generation capacity could be explored to improve upon this proxy value.

## Conclusions

This work presents a methodology for identifying and categorizing distributed wind energy installations. By combining the three defining characteristics of distributed wind—(1) small compared to centralized wind farms, (2) supply energy to loads on distribution systems or off-grid applications, and (3) proximity to load—in a sequential, replicable methodology, wind installations can be categorized as either behind the meter, intended for explicit local load, or physically distributed, and the state in which they have been installed can be tracked. This methodology helps overcome the range of existing definitions for distributed wind and the applications in which they are installed, enabling a nuanced perspective on the distributed wind energy market that other existing analyses and data sources lack.

Understanding the extent of the market within each of these categories empowers researchers and decision-makers with the data necessary to support future distributed wind deployment. It provides the information needed to tailor research and development programs and address stakeholder priorities through policies and

**Table 4** Total installed wind capacity (distributed categories plus non-distributed wind from PNNL's Project Data Set and USWTDB)

| State | Capacity (kW) | Ranking |
|---|---|---|
| AK | 72,282 | 37 |
| AL | 2 | 49 |
| AR | 104 | 44 |
| AZ | 615,383 | 27 |
| CA | 5,834,300 | 6 |
| CO | 4,878,702 | 7 |
| CT | 5815 | 41 |
| DE | 2002 | 42 |
| FL | 186 | 43 |
| GA | 7 | 48 |
| HI | 236,846 | 29 |
| IA | 11,801,863 | 2 |
| ID | 972,531 | 24 |
| IL | 6,381,631 | 5 |
| IN | 3,151,110 | 13 |
| KS | 7,324,057 | 4 |
| KY | 80 | 45 |
| LA | 60 | 46 |
| MA | 135,747 | 35 |
| MD | 191,150 | 32 |
| ME | 996,129 | 23 |
| MI | 3,225,232 | 12 |
| MN | 4,561,831 | 8 |
| MO | 2,091,843 | 18 |
| MS | 2 | 50 |
| MT | 1,115,991 | 21 |
| NC | 208,101 | 31 |
| ND | 4,268,175 | 9 |
| NE | 2,672,901 | 17 |
| NH | 214,213 | 30 |
| NJ | 9098 | 40 |
| NM | 2,838,260 | 16 |
| NV | 160,755 | 33 |
| NY | 2,083,334 | 19 |
| OH | 1,111,769 | 22 |
| OK | 9,768,519 | 3 |
| OR | 3,765,092 | 10 |
| PA | 1,459,214 | 20 |
| RI | 79,685 | 36 |
| SC | 11 | 47 |
| SD | 2,856,877 | 15 |
| TN | 28,989 | 28,989 |
| TX | 34,594,853 | 1 |
| UT | 390,700 | 28 |
| VA | 12,397 | 39 |
| VT | 150,829 | 34 |
| WA | 3,396,200 | 3,396,200 |
| WI | 737,266 | 26 |
| WV | 742,020 | 25 |
| WY | 3,136,836 | 25 |

dissemination of market information. The development of this methodology also opens researchers' ability to identify research and development priorities specific to the different categories. For example, future research could examine what type of loads and end-users may benefit the most from physically distributed wind projects or the intersection of behind-the-meter projects with urbanization. Understanding the current distributed wind energy market and categorizations is necessary to meet the existing research and development priorities of the distributed wind community and understand how distributed wind energy may evolve in the future to allow for increased deployment.

### Abbreviations

FERC: Federal Energy Regulatory Commission; PNNL: Pacific Northwest National Laboratory; PV: Photovoltaics; USWTDB: United States Wind Turbine Database.

### Acknowledgements

The authors wish to thank Sarah Barrows for her review of early versions of this manuscript.

### Author contributions

DP conceptualized the idea, conducted formal analysis, developed the methodology, validated the findings, created the visuals, wrote the original draft manuscript, and reviewed and edited the final manuscript. AO conceptualized the idea, developed the methodology, supervised the work, validated the findings, and reviewed and edited the final manuscript. EL conceptualized the idea, developed the methodology, and reviewed and edited the final manuscript. All authors read and approved the final manuscript.

### Funding

This work was supported by the U.S. Department of Energy's Wind Energy Technologies Office. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof. Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC05-76RL01830. This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding was provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy's Wind Energy Technologies Office. The U.S. Government retains, and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

### Availability of data and materials

The PNNL Project Data Set can be found at https://wind.pnnl.gov/dw_download/logon.aspx, an open-source online data download tool hosted at PNNL [24]. The USWTDB can be found at https://doi.org/10.5066/F7TX3DN0, an open-source online database hosted at the United States Geological Survey [25].

## Declarations

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Competing interests

The authors declare that they have no competing interests.

### Author details

[1]Pacific Northwest National Laboratory, 902 Battelle Boulevard, Richland, WA, USA. [2]National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO, USA.

Received: 28 February 2022 Accepted: 1 July 2022

### References

1. Executive Office of the President (2021) Executive Order 14008 Tackling the Climate Crisis at Home and Abroad. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/. Accessed 7 February 2022
2. United Nations (2015) Adoption of the Paris Agreement. In: Conference of the Parties, Twenty-first Session. https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf. Accessed 7 February 2022
3. Barbose G, Darghouth N, O'Shaugnessy E, Forrester S (2020) Distributed Solar 2020 Data Update. https://doi.org/10.2172/1735556
4. Wiser R, Bolinger M, Hoen B, Millstein D, Rand J, Barbose G, Darghouth N, Gorman W, Jeong S, Mills A, Paulos B (2021) Land-Based Wind Market Report: 2021 Edition. https://doi.org/10.2172/1818277
5. Drugmand D, Stori V (2017) Distributed Wind Energy Zoning and Permitting. https://www.cesa.org/wp-content/uploads/Distributed-Wind-Toolkit.pdf. Accessed 29 April 2022
6. Lantz E, Sigrin B, Gleason M, Preus R, Baring-Gould I (2016) Assessing the future of distributed wind: opportunities for behind-the-meter projects. https://doi.org/10.2172/1333625
7. Orrell AC, Poehlman EA (2017) Benchmarking U.S. Small Wind Costs with the Distributed Wind Taxonomy. https://doi.org/10.2172/1400355
8. Tinnesand H, Kotamarthi R, Linn R, Orrell A (2020) Distributed Wind Tools Assessing Performance. https://www.energy.gov/sites/default/files/2020/02/f72/tap-fact-sheet_0.pdf. Accessed 7 February 2022
9. Ford R, Maidment C, Vigurs C, Fell MJ, Morris M (2021) Smart local energy systems (SLES): a framework for exploring transition, context, and impacts. Technol Forecast Soc Change 166:120612. https://doi.org/10.1016/j.techfore.2021.120612
10. Thomas A, Erickson JD (2021) Rethinking the geography of energy transitions: low carbon energy pathways through energyshed design. Energy Res Soc Sci 74:101941. https://doi.org/10.1016/j.erss.2021.101941
11. Ackermann T, Andersson G, Soder L (2001) Distributed generation: a definition. Electric Power Syst Res 57:195–204. https://doi.org/10.1016/S0378-7796(01)00101-8
12. North American Electric Reliability Corporation (2017) Distributed Energy Resources: Connection Modeling and Reliability Considerations. https://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/Distributed_Energy_Resources_Report.pdf. Accessed 7 February 2022
13. Federal Energy Regulatory Commission (2018) Distributed Energy Resources: Technical Considerations for the Bulk Power System. https://www.ferc.gov/sites/default/files/2020-05/der-report_0.pdf. Accessed 7 February 2022
14. NARUC Staff Subcommittee on Rate Design (2016) Distributed Energy Resources Rate Design and Compensation. https://pubs.naruc.org/pub/19FDF48B-AA57-5160-DBA1-BE2E9C2F7EA0#:~:text=DER%20are%20resources%20located%20on,generation%20into%20the%20distribution%20grid. Accessed 7 February 2022
15. Orrell A, Baring-Gould I (2020) IEA Wind Task 41: Enabling Wind as a Distributed Energy Resource. https://iea-wind.org/wp-content/uploads/2021/02/IEA_Task_41_Fact_Sheet.pdf. Accessed 7 February 2022
16. Orrell A, Preziuso D, Foster N, Morris S, Homer J (2019) 2018 Distributed Wind Market Report. https://doi.org/10.2172/1592335
17. Distributed Wind Energy Association (2021) What is Distributed Wind?. https://distributedwind.org/home/learn-about-distributed-wind/what-is-distributed-wind/. Accessed 7 February 2022
18. Zinaman O, Aznar A, Linvill C, Darghouth N, Dubbeling T, Bianco E (2017) Grid-Connected Distributed generation: compensation mechanism basics. https://www.nrel.gov/docs/fy18osti/68469.pdf. Accessed 7 February 2022

19. National Renewable Energy Laboratory (2021) Distributed Wind Competitiveness Improvement Project. https://www.energy.gov/sites/default/files/2021/01/f82/cip-fact-sheet-2021.pdf. Accessed 7 February 2022
20. Energy Information Administration (2019) Form EIA-861 Detailed Data Files—2019. https://www.eia.gov/electricity/data/eia861/. Accessed 22 March 2021
21. Energy Information Administration (2019) Form EIA-860 Detailed Data Files—2019. https://www.eia.gov/electricity/data/eia860/. Accessed 22 March 2021
22. Walker C (2020) Using the United States wind turbine database to identify increasing turbine size, capacity and other development trends. Energy Power Eng Sci 12:407–431. https://doi.org/10.4236/epe.2020.127025
23. Orrell A, Kazimierczuk K, Sheridan L (2021) Distributed Wind Market Report: 2021 Edition. https://doi.org/10.2172/1818843
24. Orrell A (2020) PNNL Distributed Wind Project Dataset. https://www.pnnl.gov/distributed-wind. Accessed 24 April 2022
25. Hoen BD, Diffendorfer JE, Rand JT, Kramer LA, Garrity CP, Hunt HE. United States Wind Turbine Database. https://www.sciencebase.gov/catalog/item/57bdfd8fe4b03fd6b7df5ff9. Accessed 20 November 2019
26. U.S. Government Publishing Office (2011) Chapter 12—Federal Regulation and Development of Power Subchapter I—Regulation of the Development of Water Power and Resources. Sec. 796—Definitions. https://www.govinfo.gov/content/pkg/USCODE-2011-title16/pdf/USCODE-2011-title16-chap12-subchapI-sec796.pdf. Accessed 7 February 2022
27. Federal Energy Regulatory Commission (2018) Essential Reliability Services and the Evolving Bulk-Power System: Primary Frequency Response, Order No. 842. https://www.ferc.gov/sites/default/files/2020-06/Order-842.pdf. Accessed 7 February 2022
28. Czufin S, McCaffrey J (2020) The Public Utility Regulatory Policies Act of 1978: Issue Brief. https://www.publicpower.org/system/files/documents/PURPA%20-%20January%202020.pdf. Accessed 7 February 2022
29. Moorefield L (2021) Distributed Wind Case Study: Iowa Lakes Electric Cooperative. https://www.cooperative.com/programs-services/bts/radwind/Documents/RADWIND-Iowa-Lakes-Case-Study-March-2021.pdf. Accessed 7 February 2022
30. Burns & McDonnell (2022) Blue Canyon Wind Farm. https://www.burnsmcd.com/projects/blue-canyon-wind-farm. Accessed 7 February 2022
31. E Pro Engineering & Environmental Consulting (2005) Preliminary Engineering for the Redington Wind Farm 34.5 kV Collector System and 115 kV Interconnection Facility 90 MW Facility. https://www.maine.gov/DACF/lupc/projects/windpower/redington/Documents/Section01_Development_Description/Development_Electric/E_Pro_Reports/Electrical_Power_Line_Report_Final_Draft.pdf. Accessed 7 February 2022
32. WindPower Monthly (2008) Wind directly powers cement factory. https://www.windpowermonthly.com/article/960625/wind-directly-powers-cement-factory. Accessed 13 June 2022.
33. ESRI (2010) USA Census Populated Place Points. https://www.arcgis.com/home/item.html?id=9e25e210684c4acfbab785b9c4e3ed2d. Accessed 20 November 2019.
34. National Renewable Energy Laboratory (2015) Emerging Renewables Program (California) https://openei.org/wiki/Emerging_Renewables_Program_(California). Accessed 7 February 2022
35. DSIRE (2019) Self-Generation Incentive Program. https://programs.dsireusa.org/system/program/detail/552. Accessed 7 February 2022
36. Department of the Treasury Internal Revenue Service (2021) Instructions for Form 3468 Investment Credit. https://www.irs.gov/pub/irs-pdf/i3468.pdf. Accessed 28 April 2022
37. Foster N, Orrell N, Homer J, Tagestad J (2020) The "perfect storm" for distributed wind markets. Renewable Energy 145:1033–1039. https://doi.org/10.1016/j.renene.2019.05.058
38. Minnesota: State Profile and Energy Estimates (2021) Minnesota State Energy Profile. https://www.eia.gov/state/analysis.php?sid=MN. Accessed 10 September 2021
39. Hoff S, Lindstrom A (2021). Texas and Florida had large small-scale solar capacity increases in 2020. https://www.eia.gov/todayinenergy/detail.php?id=46996. Accessed 7 February 2022

## Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.