U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

# Land-Based Wind Market Report: 2022 Edition

EXECUTIVE SUMMARY

# Disclaimer

This report is being disseminated by the U.S. Department of Energy (DOE). As such, this document was prepared in compliance with Section 515 of the Treasury and General Government Appropriations Act for fiscal year 2001 (public law 106-554) and information quality guidelines issued by DOE. Though this report does not constitute "influential" information, as that term is defined in DOE's information quality guidelines or the Office of Management and Budget's Information Quality Bulletin for Peer Review, the study was reviewed both internally and externally prior to publication. For purposes of review, the study benefited from the advice and comments of eleven industry stakeholders, U.S. Government employees, and national laboratory staff.

**NOTICE**

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at SciTech Connect: http://www.osti.gov/scitech

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
OSTI: http://www.osti.gov
Phone: 865.576.8401
Fax: 865.576.5728
Email: reports@osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service

5301 Shawnee Road
Alexandria, VA 22312
NTIS: http://www.ntis.gov
Phone: 800.553.6847 or 703.605.6000
Fax: 703.605.6900
Email: orders@ntis.gov

## Authors

This report was prepared by Lawrence Berkeley National Laboratory for the Wind Energy Technologies Office of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy.

Corresponding authors of the report are: Ryan Wiser and Mark Bolinger, Lawrence Berkeley National Laboratory. The full author list includes: Ryan Wiser, Mark Bolinger, Ben Hoen, Dev Millstein, Joe Rand, Galen Barbose, Naïm Darghouth, Will Gorman, Seongeun Jeong, and Ben Paulos.

## Acknowledgments

For their support of this ongoing report series, the authors thank the entire U.S. Department of Energy (DOE) Wind Energy Technologies Office team. In particular, we acknowledge Gage Reber and Patrick Gilman. For reviewing elements of this report or providing key input, we also thank: Manussawee Sukunta (U.S. Energy Information Administration); Andrew David (Silverado Policy Accelerator); Charlie Smith (Energy Systems Integration Group); Feng Zhao (Global Wind Energy Council); David Milborrow (consultant); John Hensley (American Clean Power Association); Mattox Hall (Vestas); Aaron Barr (Wood Mackenzie); and Patrick Gilman, Gage Reber, and Liz Hartman (DOE). For providing data that underlie aspects of the report, we thank the U.S. Energy Information Administration, BloombergNEF, Wood Mackenzie, Global Wind Energy Council, and the American Clean Power Association. Thanks also to Donna Heimiller (NREL) for assistance in mapping wind resource quality; and to Amy Howerton, Carol Laurie and Alexsandra Lemke (NREL), and Liz Hartman and Heather Doty (DOE) for assistance with layout, formatting, production, and communications. Lawrence Berkeley National Laboratory's contributions to this report were funded by the Wind Energy Technologies Office, Office of Energy Efficiency and Renewable Energy of the DOE under Contract No. DE-AC02-05CH11231. The authors are solely responsible for any omissions or errors contained herein.

# Table of Contents

# Executive Summary

Wind power additions in the United States totaled 13.4 gigawatts (GW) in 2021. Recent growth is supported by the industry's primary federal incentive—the production tax credit (PTC)—as well as a myriad of state-level policies. Long-term improvements in the cost and performance of wind power technologies have also been key drivers for wind capacity additions, even as supply chain constraints due to increased commodity and transportation costs and COVID-19 restrictions push costs higher.

Key findings from this year's *Land-Based Wind Market Report*—which primarily focuses on land-based, utility-scale wind—include:

## Installation Trends

- **U.S. wind power capacity grew at a strong pace in 2021, with 13.4 GW of new capacity added and $20 billion invested.** Cumulative wind capacity grew to nearly 136 GW by the end of 2021. In addition, 1.6 GW of existing wind plants were partially repowered in 2021, mostly by upgrading rotors and nacelle components.
- **Wind power represented the second largest source of U.S. electric-power capacity additions in 2021, at 28%, behind solar's 40%.** Wind power constituted 28% of all generation and storage capacity additions in 2021. Over the last decade, wind represented 29% of total capacity additions, and a larger fraction of new capacity in SPP (82%), ERCOT (52%), MISO (52%), and the non-ISO West (33%).[1]
- **Globally, the United States again ranked second in annual wind capacity, but remained well behind the market leaders in wind energy penetration.** Global grid-connected wind additions totaled 94 GW in 2021, yielding a cumulative 839 GW. The United States remained the second-leading market in terms of annual and cumulative capacity, behind China. A number of countries have achieved high levels of wind penetration, with wind supplying 44% of Denmark's total electricity generation in 2021, and over 20% in Ireland, Portugal, Spain, Germany, and the U.K. In the United States, wind supplied 9.1%.
- **Texas installed the most wind capacity in 2021 with 3,343 MW, followed by Oklahoma, New Mexico and Kansas; eleven states exceeded 20% wind energy penetration.** Texas also remained the leader on a cumulative basis, with nearly 36 GW of capacity. Notably, the wind capacity installed in Iowa supplied 55% of all in-state electricity generation in 2021, while South Dakota (52%), Kansas (45%), Oklahoma (41%), and North Dakota (34%) were all above 30%. Within independent system operators (ISOs),

[1] The nine regions most commonly used in this report are the Southwest Power Pool (SPP), Electric Reliability Council of Texas (ERCOT), Midcontinent Independent System Operator (MISO), California Independent System Operator (CAISO), ISO New England (ISO-NE), PJM Interconnection (PJM), and New York Independent System Operator (NYISO), and the non-ISO West and Southeast.

wind penetration (expressed as a percentage of load) was 34.8% in SPP, 24.2% in ERCOT, 12.0% in MISO, 8.4% in CAISO, 3.5% in PJM, 3.0% in ISO-NE, and 2.7% in NYISO.

- **Hybrid wind plants that pair wind with storage and other resources saw limited growth in 2021, with just two new projects completed.** There were 41 hybrid wind power plants in operation at the end of 2021, representing 2.4 GW of wind and 0.9 GW of co-located assets. The most common wind hybrid project combines wind and storage technology, where 1.4 GW of wind has been paired with 0.2 GW of battery storage. The average storage duration of these projects is 0.6 hours, suggesting a focus on ancillary services and limited capacity to shift large amounts of energy across time. While only two new wind hybrids were commissioned in 2021, solar hybrids expanded rapidly with 67 new PV+storage projects coming online in 2021.
- **A record-high 247 GW of wind power capacity now exists in transmission interconnection queues, but solar and storage are growing at a much more rapid pace.** At the end of 2021, there were 247 GW of wind capacity seeking transmission interconnection, including 77 GW of offshore wind and 19 GW of hybrid wind projects (in the latter case, mostly wind paired with storage). In 2021, 73 GW of wind capacity entered interconnection queues. Energy storage interconnection requests have increased rapidly in recent years, both for stand-alone and hybrid plants, most-often pairing solar with storage. The West (non-ISO), SPP, and NYISO regions had the greatest quantity of wind in their queues at the end of 2021. Roughly one-third of all wind capacity added to queues in 2021 was for offshore wind plants.

## Industry Trends

- **Just four turbine manufacturers, led by GE, supplied all of the U.S. wind power capacity installed in 2021.** In 2021, GE captured 47% of the U.S. market for turbine installations, followed by Vestas at 26% and Siemens-Gamesa Renewable Energy (SGRE) and Nordex, both at 13%.[2]
- **The domestic wind industry supply chain contracted in 2021, with a 50% decline in blade manufacturing capability.** Domestic nacelle assembly and tower manufacturing capability declined modestly in 2021, to an equivalent 12.3 GW and 9.2 GW per year, respectively. Blade manufacturing capability plummeted by 50%, however, as three domestic manufacturing facilities closed or idled, and stood at 4.6 GW per year. More broadly, fierce competition and supply-chain constraints resulted in low profit margins for turbine manufacturers. Nonetheless, wind-related job totals in the United States increased in 2021, to 120,164.

[2] Numerical values presented here and elsewhere may not add to 100%, due to rounding.

- **Domestic manufacturing content is strong for some wind turbine components, but the U.S. wind industry remains reliant on imports, which totaled $3.1 billion in 2021.** The United States imports wind equipment from many countries, including most prominently in 2021: Mexico, Spain, and India. Domestic content is highest for nacelle assembly (>85%) and towers (55%–70%). For blades, it declined precipitously to just 15%–25% in 2021 as competitive pressures made blade imports more economical than domestically produced blades.
- **Independent power producers own the majority of wind assets built in 2021, following historical trends.** Independent power producers (IPPs) own 75% of the new wind capacity installed in the United States in 2021, with the remaining assets (25%) owned by investor-owned utilities.
- **Direct retail sales and merchant offtake arrangements for wind, in combination, matched or surpassed long-term contracted wind sales to utilities in 2021.** Electric utilities either own (25%) or buy electricity (19%) from wind projects that, in total, represent 44% of the new wind capacity installed in 2021. But direct retail purchasers of wind—including corporate offtakers—account for at least 35%, while merchant/quasi-merchant projects and power marketers make up at least another 7% and 2%, respectively. The remainder (11%) is presently undisclosed.

## Technology Trends

- **Turbine capacity, rotor diameter, and hub height have all increased significantly over the long term.** To optimize project cost and performance, and thus minimize overall cost of energy, turbines continue to grow in size. The average rated (nameplate) capacity of newly installed wind turbines in the United States in 2021 was 3.0 MW, up 9% from the previous year and 319% since 1998−1999. The average rotor diameter of newly installed turbines in 2021 was 127.5 meters, a 2% increase over 2020 and 164% over 1998−1999, while the average hub height was 93.9 meters, up 4% from 2020 and 66% since 1998−1999.
- **Turbines originally designed for lower wind speed sites dominate the market, but the trend toward lower specific power has reversed over the last two years.** With growth in swept rotor area outpacing growth in nameplate capacity, there has been a decline in the average "specific power" [3] (in $W/m^2$), from 393 $W/m^2$ among projects installed in 1998–1999 to 231 $W/m^2$ among projects installed in 2021—though specific power has modestly increased over the last two years. Turbines with low specific power were originally designed for lower wind speed sites, but are now being used at many sites as the most attractive technology.

[3] A wind turbine's specific power is the ratio of its nameplate capacity rating to its rotor-swept area. All else equal, a decline in specific power should lead to an increase in capacity factor.

- **Wind turbines were deployed in somewhat lower wind-speed sites in 2021 than in the previous seven years.** Wind turbines installed in 2021 were located in sites with an average estimated long-term wind speed of 8.0 meters per second at a height of 100 meters above the ground—this is the lowest average long-term wind speed among newly built projects in the last eight years. Federal Aviation Administration (FAA) and industry data on projects that are either under construction or in development suggest that the sites likely to be built out over the next few years will, on average, have even lower average wind speeds. Increasing hub heights help to partially offset these trends, enabling turbines to access higher wind speeds.
- **Low-specific-power turbines are deployed on a widespread basis; taller towers are seeing increased use in a wider variety of sites.** Low specific power turbines continue to be deployed in all regions, and at both lower and higher wind speed sites. The tallest towers (i.e., those above 100 meters) are found in greater relative frequency in the upper Midwest and Northeastern regions.
- **Wind projects planned for the near future are poised to continue the trend of ever-taller turbines.** The average "tip height" (from ground to blade tip extended directly overhead) among projects that came online in 2021 is 517 feet (158 meters). FAA data suggest that future projects will deploy even taller turbines. Among "proposed" turbines in the FAA permitting process, the average tip height reaches an average of 643 feet (196 meters).
- **In 2021, twelve wind projects were partially repowered, most of which now feature significantly larger rotors and lower specific power ratings.** Partially repowered projects in 2021 totaled 1.6 GW prior to repowering, a decline from the roughly 3 GW of projects partially repowered in each of the previous two years. Of the changes made to the turbines, larger rotors dominated, reducing specific power from 312 to 223 $W/m^2$. The primary motivations for partial repowering have been to re-qualify for the PTC, while at the same time increasing energy production and extending the useful life of the projects.

## Performance Trends

- **The average capacity factor in 2021 was 35% on a fleet-wide basis and 39% among wind projects built in recent years.** The average 2021 capacity factor among projects built from 2014 to 2020 was 39%, compared to an average of 26% among projects built from 2004 to 2011, and 19% among projects built from 1998 to 2001. This improvement among more-recently built projects has pushed the cumulative fleet-wide capacity factor higher over time; it was 35% in 2021. The 2021 capacity factor for projects built in 2020 was 38%, somewhat lower than for projects built from 2014 to 2020.
- **State and regional variations in capacity factors reflect the strength of the wind resource; capacity factors are highest in the central part of the country.** Based on

projects built from 2016 to 2020, average capacity factors in 2021 were highest in central states and lower closer to the coasts. Not surprisingly, the state and regional rankings are roughly consistent with the relative quality of the wind resource in each region.

- **Turbine design and site characteristics influence performance, with declining specific power leading to sizable increases in capacity factor over the long term.** The decline in specific power has been a major contributor to higher capacity factors but has been offset in part by a tendency toward building projects at sites with lower annual average wind speeds. As a result, average capacity factors over the last eight years have been reasonable stable, with some evidence of modest declines most recently as specific power has drifted upwards and site quality has modestly decreased.
- **Wind power curtailment in 2021 across seven regions averaged 4.8%, up from a low of 2.1% in 2016.** Across all ISOs, wind energy curtailment in 2021 stood at 4.8%—generally rising over the last five years. This average masks variation across regions and projects. SPP (6.4%), ERCOT (5.2%), and MISO (4.7%) experienced the highest rates of wind curtailment, while the other four ISOs were each at 2% or less.
- **2021 was an average wind resource year across most of the country.** The strength of the wind resource varies from year to year; moreover, the degree of inter-annual variation differs from site to site (and, hence, also region to region). This temporal and spatial variation impacts project performance from year to year. In 2021, the national wind index stood at its long-term average, as most regions experienced a fairly average wind year (CAISO and NYISO excepted).
- **Wind project performance degradation also explains why older projects did not perform as well in 2021**. Capacity factor data suggest some amount of performance decline with project age, though perhaps mostly once projects age beyond 10 years. The apparent decline in capacity factors as projects progress into their second decade partially explains why older projects—e.g., those built from 1998 to 2001—did not perform as well as newer projects in 2021. From year 15 to 20, project performance appears to average roughly 75% of early-year performance.

## Cost Trends

- **Wind turbine prices increased by an average of 5% to 10% in 2021 given supply chain pressures.** Wind turbine prices declined by 50% between 2008 and 2020. However, recent supply-chain pressures and rising commodity prices led to increased turbine prices in 2021. Data indicate recent pricing generally in the range of $800/kW to $950/kW,[4] roughly 5% to 10% higher than a year prior.

[4] All cost figures presented in the report are denominated in real 2021 dollars.

- **Installed project costs in 2021 held steady at an average of $1,500/kW even as turbine prices rose.** The capacity-weighted average installed cost within a sample of 2021 projects stood at $1,500/kW. This is a decrease of more than 40% from the peak in average costs in 2009 and 2010, but is roughly on par with the costs experienced in the early 2000s—albeit with much larger turbines and improved performance today. Installed costs have largely held steady over the last four years. Given the time-lag between turbine orders and project commissioning, installed project costs may rise in 2022.
- **Installed costs differed by region, from $1,350/kW to $1,600/kW.** ERCOT and the (non-California) Western states hosted the lowest-cost projects built in 2021, with average costs of $1,350/kW and $1,380/kW respectively. Higher average costs were experienced in other regions for projects installed in 2021; for example, average costs in SPP and MISO were $1,500/kW and $1,600/kW, respectively.
- **Installed costs (per megawatt) generally decline with project size; are lowest for projects over 200 MW.** Installed costs exhibit economies of scale, with costs declining as project capacity increases.
- **Operations and maintenance costs varied by project age and commercial operations date.** Despite limited data availability, projects installed over the past 15 years have, on average, incurred lower operations and maintenance (O&M) costs than older projects in their first years of operation. The data also suggest that O&M costs tend to increase as projects age, at least for the older projects in the sample.

## Power Sales Price and Levelized Cost Trends

- **Wind power purchase agreement prices have been drifting higher since about 2018, with a recent range from below $20/MWh to more than $30/MWh.** The combination of declining CapEx and OpEx and improved performance drove wind PPA prices to all-time lows through 2018, though prices have since stabilized and even increased somewhat—in part due to supply-chain pressures and perhaps also due to the ongoing phase-down of the PTC. In the Central region of the country, recent pricing is around $20/MWh. In the West and East, prices tend to average above $30/MWh.
- **LevelTen Energy's PPA price indices confirm rising PPA prices, and regional variations.** In contrast to the PPAs summarized above, which principally involve utility purchasers, LevelTen Energy provides an index of wind PPA offers made to large, end-use customers. These data also show that prices have generally risen over the last couple years, and vary by ISO. Among regions reporting data, CAISO features the highest pricing (~$52/MWh once converted to 2021 dollar terms); the lowest prices are found in ERCOT and SPP (~$25/MWh in 2021 dollars). In real dollar terms, LevelTen's reported price trends since 2018 are similar to the real-dollar denominated PPA trends described in the prior section.

- **The (unsubsidized) average levelized cost of wind energy has fallen to around $32/MWh.** Trends in the levelized cost of energy (LCOE) generally follow PPA trends, at least over the long term. Wind's LCOE generally decreased from 1998 to 2005, rose through 2009, and then declined through 2018, with a subsequent plateau over the last several years. The national average LCOE of wind projects built in 2021—excluding the PTC—was $32/MWh. As supply chain pressures continue, LCOE may be expected to rise in the near term.
- **Levelized costs vary by region, with the lowest costs in ERCOT, SPP, and the non-ISO West.** The lowest LCOEs for projects constructed in 2021—only considering regions with a larger sample—are found in ERCOT ($28/MWh), SPP ($30/MWh), and the non-ISO West ($29/MWh).

## Cost and Value Comparisons

- **Despite low PPA prices, wind faces competition from solar and gas.** The once-wide gap between wind and solar PPA prices has narrowed considerably in recent years, as solar prices have fallen more rapidly than wind prices. With the support of federal tax incentives, both wind and solar PPA prices are now below the projected cost of burning natural gas in gas-fired combined cycle units.
- **The grid-system market value of wind rebounded in 2021 to levels last seen in 2018, and is roughly consistent with recent PPA prices of under $20/MWh to $40/MWh.** Following the sharp drop in wholesale electricity prices (and, hence, wind energy market value) in 2009, average wind PPA prices tended to exceed the wholesale market value of wind through 2012. Continued declines in wind PPA prices brought those prices back in line with the market value of wind in 2013, and wind has generally remained competitive in subsequent years. In 2021, wind energy value rebounded from the 2020 low associated with the pandemic. The national average market value of wind in 2021 was $26/MWh. With high natural gas and wholesale power prices so far in 2022, wind's average market value may increase again this year.
- **The grid-system market value of wind in 2021 varied by project location, from an average of $16/MWh in MISO to $48/MWh in CAISO.** Regionally, wind market value in 2021 was lowest in MISO and SPP (average of $16/MWh and $19/MWh, respectively) and highest in CAISO and ISO-NE ($48/MWh and $44/MWh). The market value across all wind projects located in ISOs spanned $7/MWh to $48/MWh in 2021 (10$^{th}$–90$^{th}$ percentile range). Within a region, transmission congestion can noticeably reduce the grid-value of wind plants. In some situations, wind patterns are locally differentiated, and can lead to value enhancements or reductions versus plants located elsewhere.
- **The grid-system market value of wind tends to decline with wind penetration, impacted by generation profile, transmission congestion, and curtailment.** The regions

with the highest wind penetrations (SPP at 35%, ERCOT at 24%, and MISO at 12%) have generally experienced the largest reduction in wind's value relative to average wholesale prices. In 2021, wind's value was roughly 40%, 50%, 60%, and 80%, lower than average wholesale prices in NYISO, MISO, SPP, and ERCOT, respectively; but was only roughly 10% lower in ISO-NE and CAISO, and ~20% lower in PJM. These value reductions were primarily caused by a combination of transmission congestion and wind generation profiles that were negatively correlated with wholesale prices. Curtailment had only a minimal impact.

- **The health and climate benefits of wind are larger than its grid-system value, and the combination of all three far exceeds the levelized cost of wind.** Wind reduces emissions of carbon dioxide, nitrogen oxides, and sulfur dioxide, providing public health and climate benefits. Nationally and considering all wind plants, these benefits can be quantified in monetary terms, averaging $80/MWh-wind in 2021. Benefits were largest, ranging from $83/MWh to $125/MWh, in the Central, Midwest, and Mid-Atlantic regions. Values were lowest in New York ($32/MWh) and New England ($28/MWh). Focusing only on the set of wind plants built in 2021, the average climate, health, and grid-system value sums to almost four times the average LCOE. Climate, health, and grid value averaged $53/MWh, $39/MWh and $24/MWh, respectively, compared to an average LCOE of $32/MWh.

## Future Outlook

- **Energy analysts project that total annual wind additions will generally decline through 2023 before rebounding.** Specifically, expected additions drop to an average of 7 GW in 2023 before increasing to as much as 13 GW in 2025. These projected trends are driven in part by expectations about the expiration of the federal PTC, and by anticipated growth in offshore wind in the mid-2020s. Near-term additions are also influenced by the cost and performance of wind technologies, corporate wind energy purchases, and state-level renewable energy policies. Limited transmission infrastructure and competition from solar dampen growth expectations, while continuing supply chain pressures also impact deployment levels.
- **Longer term, the prospects for wind energy will be influenced by the sector's ability to continue to improve its economic position even in the face of challenging competition and near-term supply chain constraints.** Corporate demand for clean energy and state-level policies will also continue to impact wind deployment, as will the buildout of transmission infrastructure and uncertain future natural gas prices. Finally, there have been recent legislative proposals for a long-term extension of the PTC and other national policies to support a clean energy transition. The fate of these proposals will impact the sector's upside potential to exceed the projections shown above.