BERKELEY LAB

LAND-BASED WIND MARKET REPORT

2024 EDITION

EXECUTIVE SUMMARY

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Preparation and Authorship

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Executive Summary

Wind power additions in the United States totaled 6.5 gigawatts (GW) of capacity in 2023.[1] Wind power growth has historically been supported by the industry's primary federal incentive—the production tax credit (PTC)—as well as numerous state-level policies. Long-term improvements in the cost and performance of wind power technologies have also been key drivers for wind additions, yielding low-priced wind energy for utility, corporate, and other power purchasers. Nonetheless, 2023 was a slow year in terms of new wind deployment, the lowest since 2014. Elevated interest rates played a role in slowing deployment, as did interconnection and siting challenges.

Passage of the Inflation Reduction Act (IRA) promises new market dynamics for wind power deployment and supply chain investments in the years ahead. IRA contains a long-term extension of the PTC at full value (assuming that wage and apprenticeship standards are met) along with opportunities for wind plants to earn two 10 percent bonus credits that add to the PTC for meeting domestic content requirements and for being in energy communities. IRA also includes new production-based and investment-based tax credits to support the build-out of domestic clean energy manufacturing and supply chains. Though it is too early to see the full impacts of IRA in historical data, IRA has increased analyst forecasts for future wind power capacity additions and has motivated many wind industry supply-chain announcements.

Key findings from this year's *Land-Based Wind Market Report*—which primarily focuses on land-based, utility-scale wind—are summarized below. Note that the sections on "Installation Trends," "Industry Trends," and "Future Outlook" often contain combined data inclusive of both offshore and land-based wind. Other sections exclusively focus on land-based wind.

Installation Trends

- **The U.S. added 6.5 GW of wind power capacity in 2023, totaling $10.8 billion of investment.** The newly installed projects in 2023 were all land-based; no offshore projects were commissioned in 2023. Development was concentrated in the Electric Reliability Council of Texas (ERCOT), Midcontinent Independent System Operator (MISO), and the Southwest Power Pool (SPP).[2] Cumulative wind capacity grew to 150 GW. In addition, 0.6 GW of existing wind plants were partially repowered in 2023, mostly by upgrading rotors (blades) and nacelle components like gearboxes and generators.
- **Wind power's contribution to total U.S. electric-power capacity additions in 2023 fell to 12%, the lowest level since 2013.** Wind power constituted 12% of all generation and storage capacity additions in 2023, behind solar (52%), natural gas (21%), and storage (13%). Over the last decade, wind represented 26% of total capacity additions, and a larger fraction of new capacity in SPP (86%), MISO (46%), ERCOT (44%), and the non-ISO West (29%).
- **Globally, the United States again ranked a distant second in annual wind capacity and remained well behind the market leaders in wind energy penetration**. Global wind additions reached a record 117 GW in 2023, yielding a cumulative 1,021 GW. The United States remained the second-leading market in terms of annual and cumulative capacity, well behind China. Many countries have achieved high wind electricity shares, with wind supplying 57% of Denmark's total electricity generation in 2023 and more than 20% in ten other countries. In the United States, wind supplied 10% of total generation.

[1] Note that this report seeks to align with American Clean Power (ACP) for annual wind capacity additions and project-level specifics, where possible. Differences in reporting exist between ACP and the Energy Information Administration.
[2] The nine regions most 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.

- **Texas once again installed the most wind capacity of any state in 2023 (1,323 MW), followed by Illinois (928 MW); twelve states exceeded 20% wind energy penetration.** Texas also remained the leader on a cumulative capacity basis, with more than 41 GW. Notably, the wind capacity installed in Iowa supplied 59% of all in-state electricity generation in 2023; twelve states achieved wind penetration levels of 20% or higher. Within independent system operators (ISOs) and other regions, wind electricity shares (expressed as a percentage of electricity demand) were 37.1% in SPP, 24.1% in ERCOT, 13.6% in MISO, 12.5% in the non-ISO West, and 8.5% in California Independent System Operator (CAISO), with lower shares in PJM Interconnection (PJM), ISO New England (ISO-NE), the New York Independent System Operator (NYISO), and the non-ISO Southeast.
- **Hybrid wind plants that pair wind with storage and other resources saw growth in 2023, with three new projects completed.** There were 46 hybrid wind power plants in operation at the end of 2023, representing 4.1 GW of wind and 1.1 GW of co-located generation or storage assets. The most common wind hybrid project combines wind and storage technology, where 3 GW of wind has been paired with 0.5 GW of battery storage. While the average storage duration of these projects is 1.1 hours, more-recent projects have longer storage durations, suggesting a movement towards energy shifting, rather than ancillary service, applications. In contrast to wind hybrids, solar hybrids continue to expand rapidly with 62 new PV+storage projects coming online in 2023.
- **A record-high 366 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 2023, there were 366 GW of wind seeking transmission interconnection, including 120 GW of offshore wind and 49 GW of hybrid projects (in the latter case, mostly wind paired with storage). The non-ISO West, NYISO, CAISO, and PJM had the greatest quantity of wind in their queues at the end of 2023. In 2023, 107 GW of wind capacity entered interconnection queues, 11% of which was for offshore wind plants. Storage and solar interconnection requests have increased rapidly in recent years, often pairing solar with storage. Overall, wind represented 14% of all active capacity in the queues at the end of 2023, compared to 42% for solar, 40% for storage, and 3% for natural gas.

Industry Trends

- **Four turbine manufacturers, led by GE Vernova, supplied all the U.S. utility-scale wind power capacity installed in 2023.** In 2023, GE Vernova captured 58% of the market for turbine installations, followed by Vestas with 30%, Nordex with 9%, and Siemens-Gamesa Renewable Energy (SGRE) with 4%.[3]
- **The Inflation Reduction Act has created renewed optimism about supply-chain expansion.** The number of land-based wind turbine towers and nacelles (which sit on top of the tower and house the gearbox and generator) that can manufactured domestically has held steady or increased over the last several years. At the end of 2023, domestic capacity was nearly 15 GW per year for nacelle assembly and over 12 GW per year for tower manufacturing. Domestic blade manufacturing capability, on the other hand, declined precipitously after 2020, but with a slight rebound in 2023 to over 4 GW per year. The Inflation Reduction Act holds promise for fueling supply-chain expansion in the years ahead: fifteen new, re-opened, or expanded manufacturing facilities have been announced since IRA to serve the land-based wind market, with more than 3,200 expected new jobs. As for turbine manufacturer profitability, there were signs of a turnaround in 2023, with improved profitability (or reduced losses) for Vestas, GE Vernova, and Nordex.
- **The U.S. wind industry continues to depend on imports, though these have fallen to their lowest level in a decade.** Wind-related imports decreased to $1.7 billion in 2023 from $2.3 billion in 2022, mirroring the decrease in annual wind capacity additions. Almost 70% of all wind-specific imports that

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

are tracked through trade codes came from Mexico, Germany, Spain, and India, with the remaining imports mostly from Canada and various countries in Europe and Asia.

- **Independent power producers own most wind assets built in 2023, extending historical trends.** Independent power producers (IPPs) own 90% of the new wind capacity installed in the United States in 2023, with the remaining assets (10%) owned by investor-owned utilities.
- **Non-utility buyers entered more contracts to purchase wind than did utilities in 2023.** Direct retail purchasers of wind—including corporate offtakers—buy electricity from at least 48% of the new wind capacity installed in 2023. This exceeds the share purchased by electric utilities, who either own or buy electricity from wind projects that, in total, represent 29% of the new capacity installed in 2023. Merchant/quasi-merchant projects and power marketers make up at least another 9% and 3%, respectively, while 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, turbines continue to grow in size. The average rated (nameplate) capacity of newly installed land-based wind turbines in the United States in 2023 was 3.4 MW, up 5% from the previous year and 375% since 1998−1999. The average rotor diameter of newly installed turbines was 133.8 meters, a 2% increase over 2022 and 178% over 1998−1999, while the average hub height was 103.4 meters, up 5% from 2022 and 83% since 1998−1999.
- **Turbines originally designed for lower wind speed sites dominate the market, but the trend towards lower specific power has moderated in recent years.** With growth in swept rotor area outpacing growth in nameplate capacity, there has been a decline in the average "specific power" [4] (in W/m^2), from 393 W/m^2 among projects installed in 1998–1999 to 237 W/m^2 among projects installed in 2023—though specific power has modestly increased over the last four years. Turbines with low specific power ratings were originally designed for lower wind speed sites.
- **Wind turbines were deployed in lower wind-speed sites in 2023 than in recent years.** Wind turbines installed in 2023 were located in sites with an average estimated long-term wind speed of 7.9 meters per second at a height of 100 meters above the ground—the lowest site-average wind speed since 2012. 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 consistent or lower average wind speeds. Increasing hub heights will help to partially offset this trend, however, enabling turbines to access higher wind speeds than otherwise possible with shorter towers.
- **Low-specific-power turbines are deployed on a widespread basis throughout the country; taller towers are seeing increased use in a wider variety of sites.** Low specific power turbines continue to be deployed at both lower and higher wind speed sites and across all regions. The tallest towers (i.e., those above 110 meters) are found in greater relative frequency in the 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 2023 is 170 meters. FAA data suggest that future land-based projects will deploy even taller turbines. Among "proposed" turbines in the permitting process, the average tip height reaches 206 meters.
- **In 2023, seven wind projects were partially repowered, all of which now feature significantly larger rotors and lower specific power ratings.** Partially repowered projects in 2023 totaled 630 MW prior to repowering (640 MW after), a substantial decrease from the 1.7 GW of projects partially repowered in

[4] 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.

2022. Of the changes made to the turbines, larger rotors dominated, reducing specific power from 325 to 213 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 2023 was 33.5% on a fleet-wide basis and 38.2% among wind plants built in 2022.** The 38.2% capacity factor for land-based projects was higher than for projects built in 2021 but consistent with averages for projects built over the last decade. Cumulative, fleet-wide performance has tended to increase over time, growing from under 27% in 1999 to 36% in 2022. However, 2023 was a low wind year nationally, driving down fleet-wide capacity factors in 2023 to 33.5%.
- **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 2017 to 2022, average capacity factors in 2023 were highest in central states and lower closer to the coasts. Not surprisingly, the relative state and regional capacity factors 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 over the last two decades 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 have been relatively stable among projects built over the last ten years.
- **Wind power curtailment in 2023 varied by region, averaging 4.6% across seven ISOs**. Across all ISOs, wind energy curtailment in 2023 stood at 4.6%, a decline from 2022 but higher than a decade ago. This average masks variation across regions (and projects): SPP (8.3%), ERCOT (4.2%), NYISO (3.3%), and MISO (3.2%) experienced the highest rates of wind curtailment in 2023, while the other three ISOs were each at less than 2%.
- **2023 was a low 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 2023, the national wind index stood at 0.95, its lowest level since 2005, as most regions experienced a below-average wind year.
- **Wind project capacity factors decline as projects age.** Capacity factor data suggest performance decline with project age. The decline is present in both older and newer projects in the sample. By year 20, the median wind project has a capacity factor that is roughly 70% that of year 2.

Cost Trends

- **Wind turbine prices modestly declined in 2023, averaging roughly $1,000/kW.** Wind turbine prices for land-based projects declined by more than 50% between 2008 and 2020. Supply-chain pressures and elevated commodity prices led to increased turbine prices from 2020 to 2022—trends that began to moderate in 2023, with prices flat or somewhat lower than in 2022. Data indicates that average pricing over the last year ranges from $900/kW to $1,100/kW.[5]
- **Despite recent fluctuations in turbine prices, average reported installed project costs have held surprisingly steady since 2018**. The average installed costs of land-based wind projects declined from the beginning of the U.S. wind industry in the 1980s through the early 2000s, and then increased—reflecting turbine price changes—through the latter part of that decade before peaking in 2009–2010.

[5] All cost figures presented in the report are denominated in real 2023 dollars.

Project-level costs have since declined back to levels seen in the early 2000s—and, since 2018, have largely held steady at ~$1,700/MW on a capacity-weighted average basis.

- **Recent installed costs differ by region, with SPP and ERCOT featuring the lowest costs.** The lowest-cost projects installed in 2022 and 2023 have been in SPP (averaging $1,320/kW) and ERCOT (averaging $1370/kW). Higher average costs are observed in MISO, the non-ISO West, and PJM.
- **Installed costs (per megawatt) generally decline with project size, and are lowest for projects over 200 MW.** Installed project costs exhibit economies of scale, with an especially apparent drop in average costs for the largest (> 200 MW) projects in the sample.
- **Operations and maintenance costs varied by project age and commercial operations date.** Despite limited data, projects installed over the last decade and a half have, on average, incurred lower operations and maintenance (O&M) costs than the oldest projects in the data sample.

Power Sales Price and Levelized Cost Trends

- **Wind power purchase agreement prices have drifted higher since about 2018, with a recent range from below $20/MWh to more than $40/MWh.** The combination of declining capital and operating costs and improved performance drove land-based wind PPA prices to all-time lows through 2018, but prices have since increased—in part due to supply-chain and other inflationary pressures. Though our sample size in the last few years has been small, pricing in 2021 and 2022 appears to have averaged around $25/MWh in the Central and West regions of the country, with higher prices in the East (~$45/MWh).
- **LevelTen Energy's PPA price indices confirm rising PPA prices and regional variation.** In contrast to the PPAs summarized above, which principally involve utility purchasers, the company LevelTen Energy provides an index of PPA offers made to large, end-use customers. These data also show that prices have risen over the last couple of years and vary by ISO. Among regions reporting data, CAISO features the highest pricing (~$65/MWh in the fourth quarter of 2023 once converted to levelized 2023-dollar terms); the lowest prices are found in SPP and ERCOT (~$35/MWh in 2023 dollars).
- **Among a sample of projects built in 2023, the (unsubsidized) average levelized cost of wind energy is estimated to be $49/MWh.** Trends in the levelized cost of energy (LCOE) of land-based wind projects follow PPA trends, at least over the long term. Wind's LCOE decreased from 1998 to 2005, rose through 2008-2011, declined through 2018, but has then held steady or increased—to $49/MWh among a sample 2023 projects. The rise in LCOE in 2023 is due, in part, to a higher cost of capital and to a decrease in average capacity factors. As more data become available, the average LCOE among recent wind plants could be revised.
- **Levelized costs vary by region, with the lowest costs in SPP and ERCOT**. The lowest average LCOEs for projects built in 2022 and 2023 are found in SPP ($37/MWh on average) and ERCOT ($42/MWh), with PJM, MISO, and the non-ISO West averaging around $47–49/MWh.

Cost and Value Comparisons

- **Despite relatively low PPA prices, wind faces competition from solar and gas.** The once-wide gap between land-based wind and solar PPA prices has narrowed, as solar prices have fallen more rapidly over the last decade. With the support of federal tax incentives, both wind and solar PPA prices are on par with or below the projected cost of burning natural gas in gas-fired combined cycle units.
- **The grid-system market value of wind declined in 2023 across all regions and was often lower than recent wind PPA prices.** Average land-based wind PPA prices tended to well exceed the wholesale market value of wind from 2008 to 2012. With continued declines in PPA prices, however, those prices connected with the market value of wind in 2013 and have remained in competitive territory in subsequent years. With the increase in natural gas and electricity prices, 2022 wind market values rose to

levels last seen in 2014 in several regions and were higher than recent PPA prices in many locations. However, those high market values for wind were temporary, with 2023 seeing a steep decline in natural gas prices and wind's market value across all ISO regions.

- **The grid-system market value of wind in 2023 varied strongly by project location, from an average of $13/MWh in SPP to $60/MWh in CAISO.** Regionally, wind market value in 2023 was highest in CAISO ($60/MWh) and ISO-NE ($36/MWh). PJM ($25/MWh), NYISO ($23/MWh), and ERCOT ($23/MWh) were the next highest markets. The average market value of wind was the lowest in SPP ($13/MWh) and MISO ($17/MWh). The market value across all wind projects located in ISOs spanned $7/MWh to $52/MWh in 2023 ($10^{th}$–$90^{th}$ percentile range). Within a region, transmission congestion can noticeably reduce the grid value of wind plants.

- **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 37%, ERCOT at 24%, and MISO at 14%) have generally experienced the largest reduction in wind's value relative to average wholesale prices. In 2023, wind's value was roughly 40%, 40%, 50%, and 60%, lower than average wholesale prices in NYISO, MISO, ERCOT, and SPP, 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 hourly wind generation that was 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 nearly all wind plants, these health and climate benefits can be quantified in monetary terms, averaging $162 per MWh of wind in 2023. Combined, the national average climate, health, and grid-system value of wind ($183/MWh) sums to more than three times the average LCOE of plants built in 2023.

Future Outlook

- **Energy analysts project growing wind deployment, spurred by incentives in the Inflation Reduction Act.** Expected total capacity additions, inclusive of land-based and offshore wind, range from 7.3 GW to 9.9 GW in 2024. Expected additions then increase, supported by expanded incentives in the Inflation Reduction Act as well as anticipated growth in offshore wind. In 2028, expected total additions range from 14.5 GW to 24.8GW. The majority of the expected additions over this 5-year period and in 2028 come from land-based wind, with offshore wind averaging 11% of the total. Despite this anticipated growth, headwinds remain: inflation, higher interest rates, limited transmission infrastructure, interconnection costs and timeframes, siting and permitting challenges, and competition from solar may dampen growth.

- **Longer term, the prospects for wind energy will be influenced by the Inflation Reduction Act and by the sector's ability to continue to improve its economic position.** The prospects for wind energy in the longer term will be influenced by the implementation of the Inflation Reduction Act, which not only provides extensions and expansions of deployment-oriented tax credits but also new incentives for the buildout of domestic supply chains. Also influencing deployment will be the sector's ability to continue to improve its economic position even in the face of challenging competition from other generation resources, such as solar and natural gas. Growing electricity loads may further motivate additional wind power deployment. Finally, changing macroeconomic conditions, corporate demand for clean energy, and state-level policies will also continue to impact wind power deployment, as will the buildout of transmission infrastructure, resolution of siting, permitting and interconnection constraints, and the future uncertain cost of natural gas.

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Cover details: Sunrise at King Plains Wind Farm in Garber, Oklahoma. *Photo by Bryan Bechtold, NREL*