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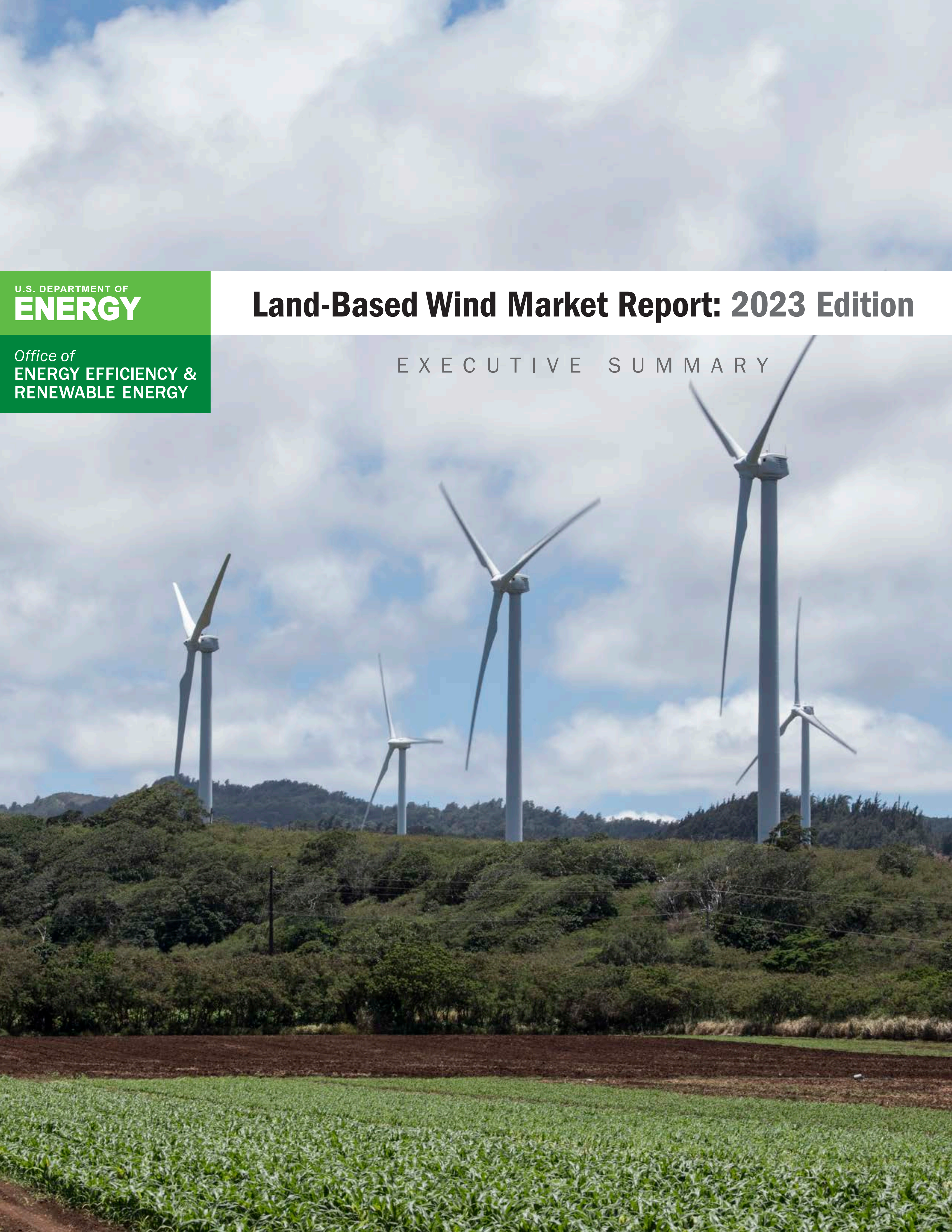
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Land-Based Wind Market Report: 2023 Edition

EXECUTIVE SUMMARY



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Cover Photo: A wind farm on the north shore of Oahu. It is operated by the Hawaiian Electric Company. Photo by Dennis Schroeder, NREL 57714

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Preparation and Authorship

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Executive Summary

Wind power additions in the United States totaled 8.5 gigawatts (GW) in 2022.[1] Wind power growth has historically been supported by the industry's primary federal incentive—the production tax credit (PTC)—as well as myriad state-level policies. Long-term improvements in the cost and performance of wind power technologies have also been key drivers for wind additions. Nonetheless, 2022 was a relatively slow year in terms of new wind power deployment—the lowest since 2018—due in part to ongoing supply chain pressures, higher interest rates, and interconnection and siting challenges, but also the reduction in the value of the PTC that was in place up until the passage of the Inflation Reduction Act (IRA) in August 2022.

Passage of 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 new 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 locating projects in energy communities. Among many other provisions, IRA also includes new production-based and investment-based tax credits to support the build-out of domestic clean energy manufacturing. Though it is too early to see the full impacts of IRA in historical data, IRA has already impacted analyst forecasts for future wind power capacity additions and 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—include:

Installation Trends

- **The U.S. added 8.5 GW of wind power capacity in 2022, totaling $12 billion of investment.** Development was concentrated in the Electric Reliability Council of Texas (ERCOT) and the Southwest Power Pool (SPP).[2] Cumulative wind capacity grew to more than 144 gigawatts (GW) by the end of 2022. In addition, 1.7 GW of existing wind plants were partially repowered in 2022 (the final, repowered capacity of these plants is 1.8 GW), mostly by upgrading rotors (blades) and nacelle components like gearboxes and generators.
- **Wind power represented the second largest source of U.S. electric-power capacity additions in 2022, at 22%, behind solar's 49%.** Wind power constituted 22% of all generation and storage capacity additions in 2022. Over the last decade, wind represented 27% of total capacity additions, and a larger fraction of new capacity in SPP (85%), ERCOT (49%), the Midcontinent Independent System Operator (MISO) (47%), and the non-ISO West (30%).
- **Globally, the United States again ranked second in annual wind capacity but remained well behind the market leaders in wind energy penetration**. Global wind additions totaled over 77 GW in 2022, yielding a cumulative 906 GW. The United States remained the second-leading market in terms of annual and cumulative capacity, behind China. Many countries have achieved high wind electricity shares, with wind supplying 57% of Denmark's total electricity generation in 2022 and more than 20% in a total of eight countries. In the United States, wind supplied about 10% of total generation.
- **Texas once again installed the most wind capacity of any state in 2022 (4,028 MW), followed by Oklahoma (1,607 MW); twelve states exceeded 20% wind energy penetration.** Texas also remained

[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.

the leader on a cumulative capacity basis, with more than 40 GW. Notably, the wind capacity installed in Iowa supplied 62% of all in-state electricity generation in 2022, followed by South Dakota (55%), Kansas (47%), Oklahoma (44%), North Dakota (37%), New Mexico (35%), and Nebraska (31%). Within independent system operators (ISOs), wind electricity shares (expressed as a percentage of load) were 37.9% in SPP, 24.8% in ERCOT, 14.5% in MISO, 8.7% in California Independent System Operator (CAISO), 4.0% in PJM Interconnection (PJM), 3.2% in ISO New England (ISO-NE), and 3.1% in New York Independent System Operator (NYISO).

- **Hybrid wind plants that pair wind with storage and other resources saw limited growth in 2022, with just one new project completed.** There were 41 hybrid wind power plants in operation at the end of 2022, representing 2.6 GW of wind and 0.8 GW of co-located generation or storage 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 one new wind hybrid—combining wind, solar photovoltaics (PV), and storage—was commissioned in 2022, solar hybrids continue to expand rapidly with 59 new PV+storage projects coming online in 2022.
- **A record-high 300 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 2022, there were 300 GW of wind capacity seeking transmission interconnection, including 113 GW of offshore wind and 24 GW of hybrid projects (in the latter case, mostly wind paired with storage). NYISO, the non-ISO West, and PJM had the greatest quantity of wind in their queues at the end of 2022. In 2022, 90 GW of wind capacity entered interconnection queues, 41% of which was for offshore wind plants. Storage and solar interconnection requests have increased rapidly in recent years, oftentimes pairing solar with storage.

Industry Trends

- **Just four turbine manufacturers, led by GE, supplied all the U.S. utility-scale wind power capacity installed in 2022.** In 2022, GE captured 58% of the market for turbine installations, followed by Vestas with 24%, Nordex with 10%, and Siemens-Gamesa Renewable Energy (SGRE) with 8%.[3]
- **The domestic wind industry supply chain began 2022 in decline, but passage of the Inflation Reduction Act has created renewed optimism about supply-chain expansion.** The number of wind turbine towers and nacelles (which sit on top of the tower and house the gearbox and generator) that we can manufacture domestically in the United States has held steady or increased over the last several years. At the end of 2022, domestic capacity was 15 GW per year for nacelle assembly and 11 GW per year for tower manufacturing. Blade manufacturing continued its decline in 2022, with under 4 GW per year of capability by the end of the year. More broadly, many turbine manufacturers continued to face declining and even negative profit margins in 2022. Nonetheless, wind-related job totals increased by 4.5% in 2022, to 125,580 full-time workers. Moreover, passage of the Inflation Reduction Act holds promise for addressing recent domestic supply-chain challenges and fueling expansion: at least eleven new, re-opened, or expanded manufacturing facilities have been announced in recent months to serve the land-based wind market, totaling more than 3,000 new jobs.
- **Domestic manufacturing content is strong for some wind turbine components, but the U.S. wind industry remains reliant on imports.** The United States imports wind equipment from many countries, including most prominently in 2022: Mexico, India, and Spain. Nonetheless, for wind projects installed in 2022, over 85% of nacelle assembly and 70%–85% of tower manufacturing occurred in the United States; in the case of towers, benefitting from import tariffs. For blades, domestic content was just 5–25% in 2022, having plummeted in recent years. How these trends change after passage of the Inflation

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

Reduction Act remains to be seen, though supply-chain announcements in recent months suggest a resurgence in domestic manufacturing.

- **Independent power producers own most wind assets built in 2022, extending historical trends.** Independent power producers (IPPs) own 84% of the new wind capacity installed in the United States in 2022, with the remaining assets (16%) owned by investor-owned utilities.
- **For the first time, non-utility buyers entered into more contracts to purchase wind than did utilities in 2022.** Direct retail purchasers of wind—including corporate offtakers—buy electricity from at least 44% of the new wind capacity installed in 2022. This ~44% share exceeds, for the first time, that of electric utilities, who either own (16%) or buy electricity from (17%) wind projects that, in total, represent 33% of the new capacity installed in 2022. Merchant/quasi-merchant projects and power marketers make up at least another 3% and 6%, respectively, while the remainder (14%) 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 wind turbines in the United States in 2022 was 3.2 MW, up 7% from the previous year and 350% since 1998−1999. The average rotor diameter of newly installed turbines was 131.6 meters, a 3% increase over 2021 and 173% over 1998−1999, while the average hub height was 98.1 meters, up 4% from 2021 and 73% since 1998−1999.
- **Turbines originally designed for lower wind speed sites dominate the market, but the trend towards lower specific power has reversed 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 233 W/m^2 among projects installed in 2022—though specific power has modestly increased over the last three 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.
- **Wind turbines were deployed in higher wind-speed sites in 2022 than in recent years.** Wind turbines installed in 2022 were located in sites with an average estimated long-term wind speed of 8.3 meters per second at a height of 100 meters above the ground—the highest site-average wind speed since 2014. 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 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; 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 2022 is 164 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 195 meters.
- **In 2022, thirteen wind projects were partially repowered, most of which now feature significantly larger rotors and lower specific power ratings.** Partially repowered projects in 2022 totaled 1.7 GW

[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.

prior to repowering (1.8 GW after), a slight increase from the 1.6 GW of projects partially repowered in 2021. Of the changes made to the turbines, larger rotors dominated, reducing specific power from 300 to 220 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 2022 was 36% on a fleet-wide basis and 37% among wind plants built in 2021.** The average 2022 capacity factor among projects built from 2013 to 2021 was 40%, compared to an average of 31% among all projects built from 2004 to 2012, and 23% among all projects built from 1998 to 2003. This has pushed the cumulative fleet-wide capacity factor higher over time, to 36% in 2022. The average 2022 capacity factor for projects built in 2021 was 37%, 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 2017 to 2021, average capacity factors in 2022 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 nine years, with some evidence of modest declines among post-2018 vintage projects as specific power has drifted upwards in the most recent several years and site quality has decreased somewhat.
- **Wind power curtailment in 2022 across seven regions averaged 5.3%, up from a low of 2.1% in 2016.** Across all ISOs, wind energy curtailment in 2022 stood at 5.3%—generally rising over the last six years. This average masks variation across regions and projects: SPP (9.2%), ERCOT (4.7%), MISO (4.4%), and NYISO (3.2%) experienced the highest rates of wind curtailment in 2022, while the other three ISOs were each at less than 2%.
- **2022 was an above-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 2022, the national wind index stood at 1.06, its highest level since 2014, as most regions experienced an above-average wind year (the non-ISO West excepted).
- **Wind project performance degradation also explains why older projects did not perform as well in 2022.** Capacity factor data suggest 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 2003—did not perform as well as newer projects in 2022.

Cost Trends

- **Wind turbine prices continued to increase in 2022, reaching roughly $1,000/kW.** Wind turbine prices declined by 50% between 2008 and 2020. However, recent supply chain pressures and elevated commodity prices have led to increased turbine prices. Data indicate recent average pricing in the range of $900/kW to $1,200/kW[5], a level roughly similar to that last seen in 2017 and 2018 and up from a range of $800-$1,000/kW for 2019–2021.

[5] All cost figures presented in the report are denominated in real 2022 dollars.

- **Surprisingly, average installed project costs among our small sample of 2022 projects did not follow turbine prices higher.** After four years of relatively stable costs of ~$1600/kW from 2018 through2021, the surprising drop in the capacity-weighted average installed cost in 2022—to $1,370/kW—is partly attributable to the outsized influence of a single large project in our relatively small 2022 plant sample and to the concentration of wind deployment in 2022 in the low-cost regions of SPP and ERCOT. The 2022 capacity-weighted average may change as more data become available over time.
- **Recent installed costs differ by region**. The lowest-cost projects in recent years have been in ERCOT (averaging $1360/kW) and SPP ($1470/kW), while MISO projects have averaged $1730/kW. Again, sample size in 2022 (and, to a lesser extent, in 2021) is abnormally low, and these averages may change as more data become available.
- **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, projects installed over the past 16 years have, on average, incurred lower operations and maintenance (O&M) costs than older projects. 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 $40/MWh.** The combination of declining capital and operating costs and improved performance drove wind PPA prices to all-time lows through 2018, though prices have since stabilized and then increased—in part due to supply-chain and other inflationary pressures. Though our sample size in the last year or two is relatively small, recent pricing appears to be around $20/MWh in the Central region of the country, a bit higher in the West (ranging from $20/MWh to $40/MWh), and higher still in the East (~$50/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, 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 (~$60/MWh in the third quarter of 2022 once converted to levelized 2022 dollar terms); the lowest prices are found in SPP and ERCOT (~$33/MWh in 2022 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.
- **Among a relatively small sample of projects built in 2022, the (unsubsidized) average levelized cost of wind energy has fallen to around $32/MWh.** Trends in the levelized cost of energy (LCOE) follow PPA trends, at least over the long term. Wind's LCOE decreased from 1998 to 2005, rose through 2009-2011, declined through 2018, but has remained steady over the last several years. The national average LCOE among a small sample of projects built in 2022—excluding the PTC—was $32/MWh. This average is impacted by the concentration of projects installed in 2022 in the windy, low-cost regions of ERCOT and SPP. As more data become available, the average LCOE among 2022 (and 2021) 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 2021 and 2022—only considering regions with at least two plants in the sample—are found in SPP and ERCOT (both ~$33/MWh on average), with PJM averaging the highest at $46/MWh.

Cost and Value Comparisons

- **Despite relatively low PPA prices, wind faces competition from solar and gas.** The once-wide gap between wind and solar PPA prices has narrowed, as solar prices have fallen more rapidly than wind prices 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 surged in 2022 across many regions and was often higher than recent wind PPA prices .** 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 2022, wind energy value remained at elevated levels after having rebounded in 2021 from the low associated with the pandemic. The national average market value of wind in 2022 was $32/MWh. With lower natural gas prices so far in 2023, wind's average market value may decline this year.
- **The grid-system market value of wind in 2022 varied strongly by project location, from an average of $18/MWh in SPP to $83/MWh in ISO-NE.** Regionally, wind market value in 2022 was lowest in SPP (average of $18/MWh) and highest in ISO-NE and CAISO ($83/MWh and $76/MWh). The market value across all wind projects located in ISOs spanned $12/MWh to $77/MWh in 2022 (10th–90th 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 38%, ERCOT at 25%, and MISO at 14%) have generally experienced the largest reduction in wind's value relative to average wholesale prices. In 2022, wind's value was roughly 40%, 50%, 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 ~20% lower in CAISO and 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 all wind plants, these health and climate benefits can be quantified in monetary terms, averaging $135 per MWh of wind in 2022 (based on updated methods and damage assumptions—see the full report and Appendix). These benefits were largest in the Central ($200/MWh), Midwest ($133/MWh), Texas ($111/MWh), and Western ($109/MWh) regions, and were lowest in New York ($58/MWh), New England ($83/MWh), and the Mid-Atlantic ($89/MWh). Combined, the national average climate, health, and grid-system value sums to five times the average LCOE of plants built in 2022. Specifically, climate, health, and grid value averaged $99/MWh, $37/MWh, and $32/MWh, respectively, compared to an average LCOE of $32/MWh.

Future Outlook

- **Energy analysts project growing wind deployment, spurred by incentives in the Inflation Reduction Act .** Expected capacity additions range from 7.1 GW to 12 GW in 2023. Expected additions then increase rapidly, supported by expanded incentives in the Inflation Reduction Act as well as anticipated growth in offshore wind. By 2027, expected additions range from 18.4 GW to 22.7 GW. The influence of the IRA—most importantly, its long-term extension of the PTC along with opportunities for wind plants to earn bonus credits if meeting domestic content requirements and/or located in an energy community—dominates analyst forecasts. For example, the average deployment forecast for 2026 is 18 GW, compared to 11 GW one year ago, pre-IRA. But headwinds remain: inflation, higher interest rates, limited transmission infrastructure, interconnection costs and timeframes, siting and permitting challenges, and competition from solar may dampen growth, as may any continuing supply chain pressures.

- **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. The speed with which supply chain constraints are addressed will impact deployment volumes. Changing macroeconomic conditions, corporate demand for clean energy, and state-level policies will also continue to impact wind growth, as will the buildout of transmission infrastructure, resolution of siting, permitting and interconnection constraints, and the future uncertain cost of natural gas.