U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Land-Based Wind Market Report: 2022 Edition

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Land-Based Wind Market Report: 2022 Edition

Purpose and Scope:

- Summarize data on key trends in the U.S. wind power sector
- Focus on land-based wind turbines over 100 kW in size
  - Separate DOE-funded data collection efforts on distributed and offshore wind
  - Note that the *Installation Trends*, *Industry Trends*, and *Future Outlook* sections include data on both land-based and offshore wind; other chapters focus solely on land-based
- Focus on historical data, with some emphasis on the previous year

Funding:

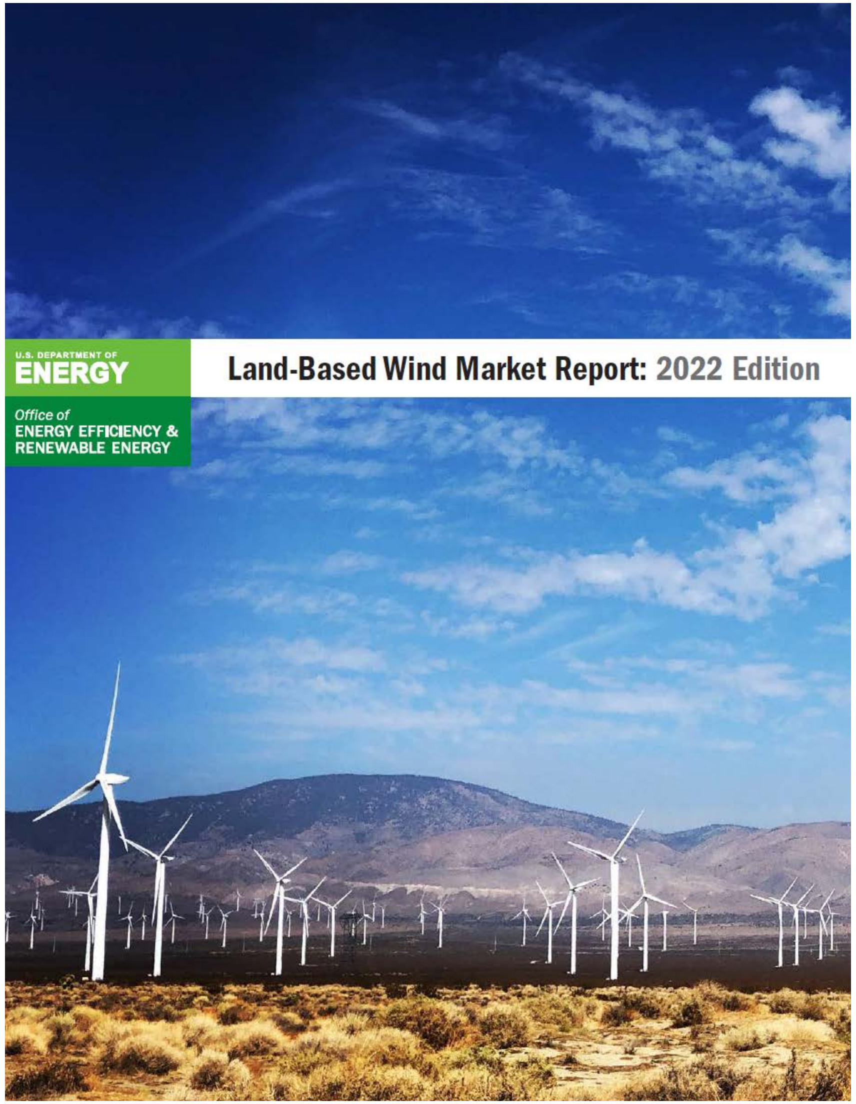
- U.S. Department of Energy's Wind Energy Technologies Office

Products and Availability:

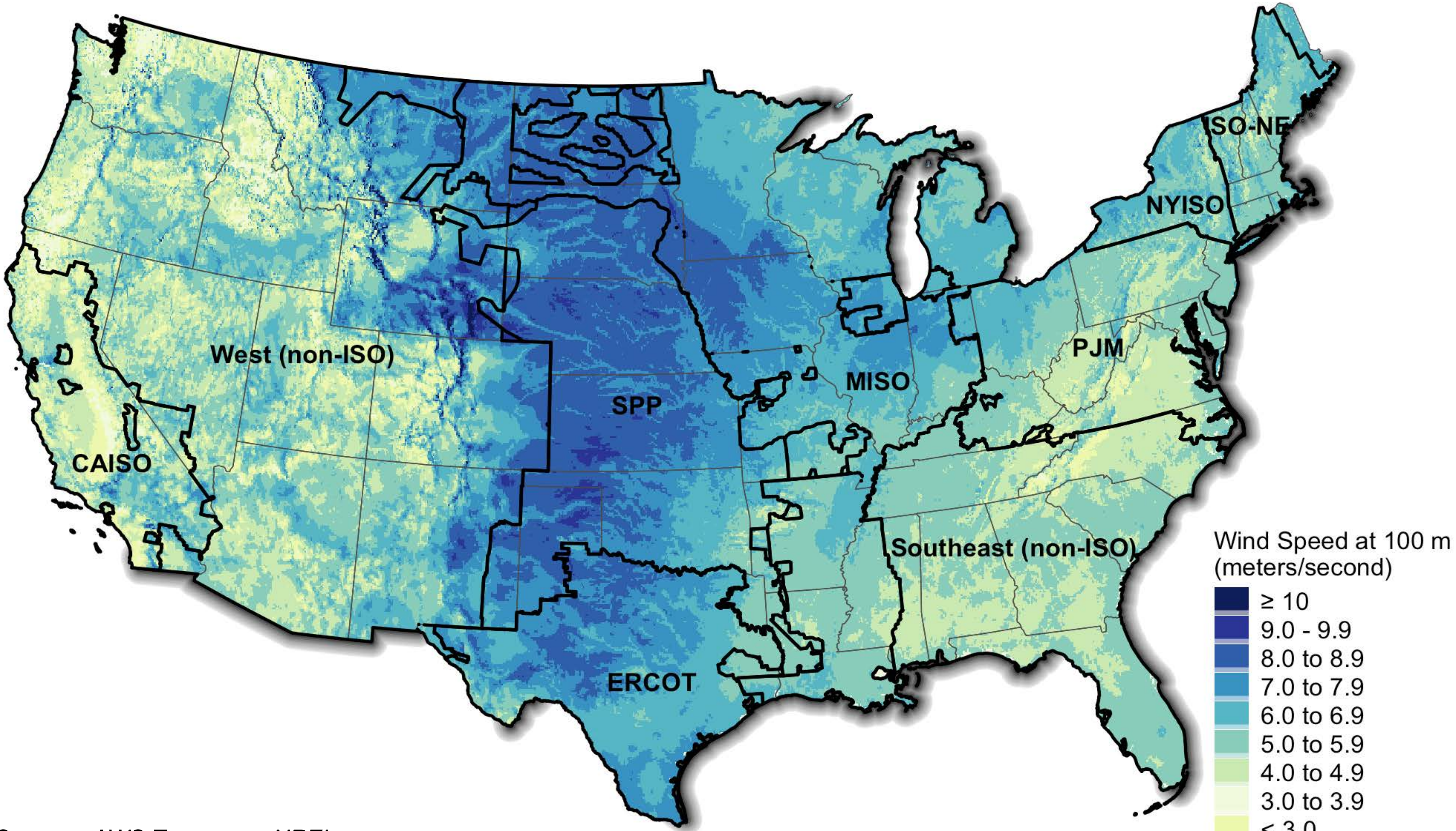
- This briefing is complemented with underlying report, data file, and visualizations
- All products available at: windreport.lbl.gov

Presentation Contents

- Installation trends
- Industry trends
- Technology trends
- Performance trends
- Cost trends
- Power sales price and levelized cost trends
- Cost and value comparisons
- Future outlook



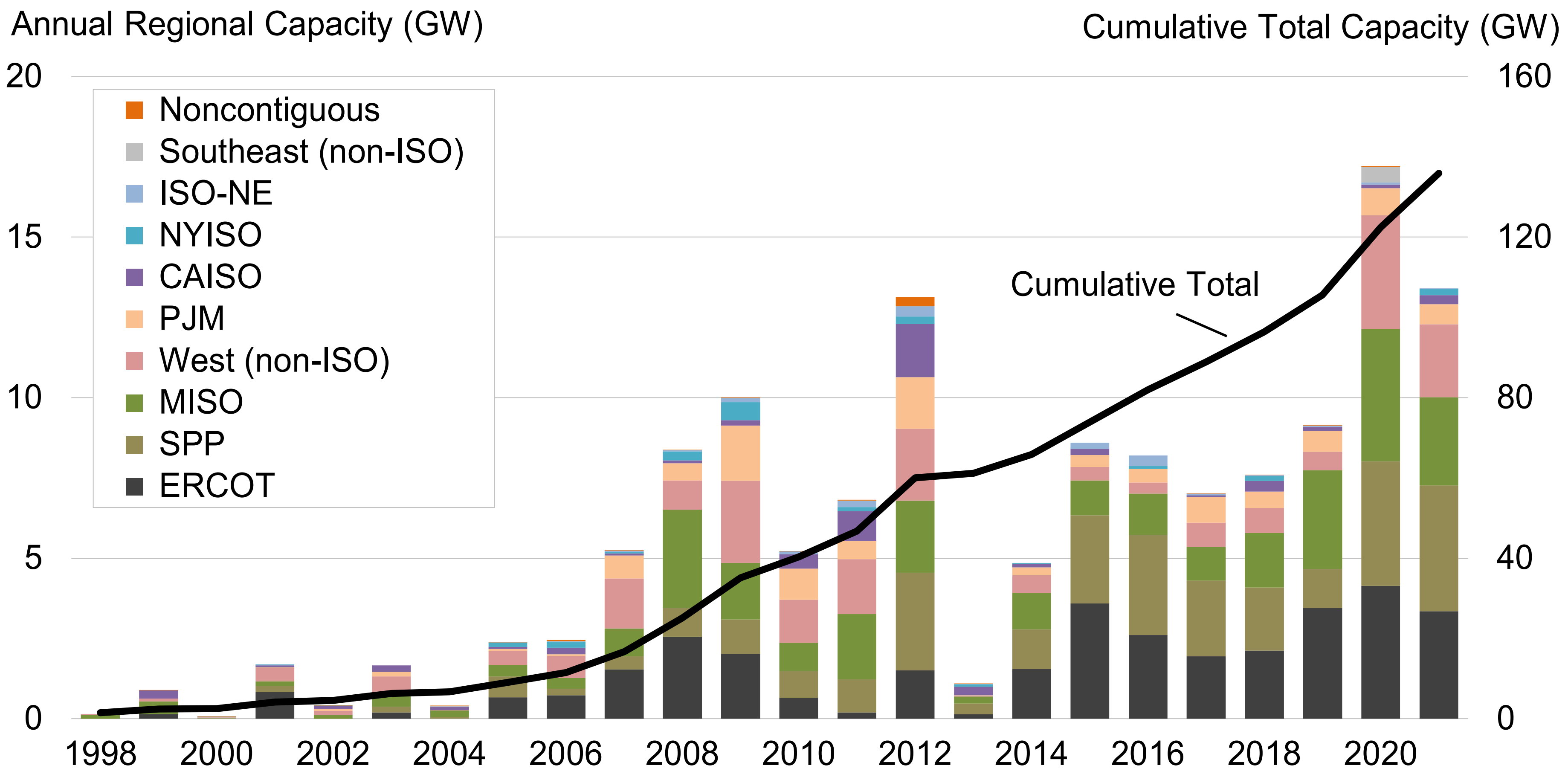
Regional boundaries applied in this analysis include the seven independent system operators (ISO) and two non-ISO regions



Sources: AWS Truepower, NREL

Installation Trends

Wind power capacity grew at a strong pace in 2021, with 13.4 GW of new capacity added and $20 billion invested



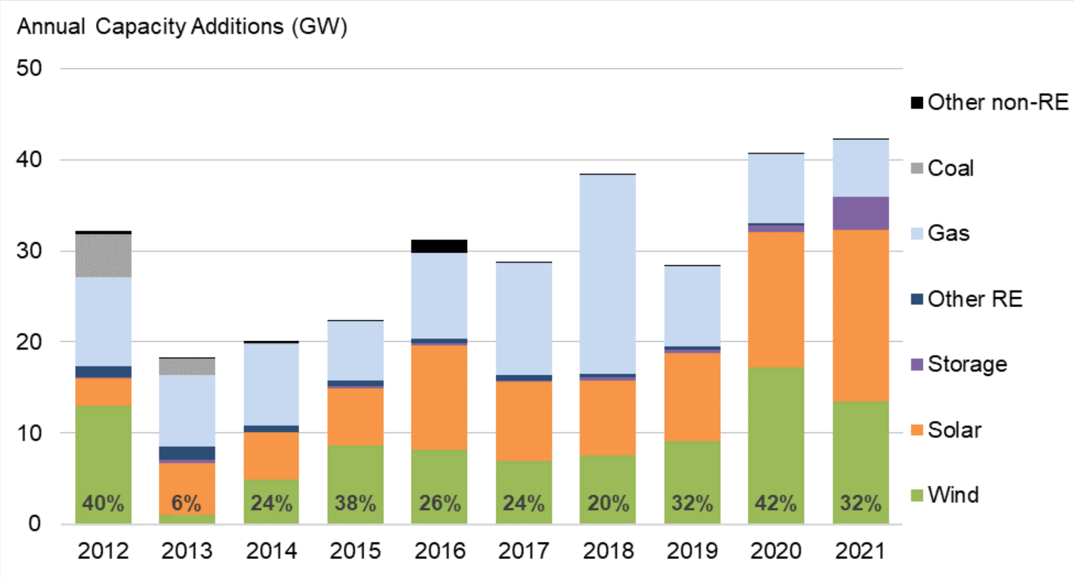
Source: ACP

- ~75% of new capacity in ERCOT, MISO, SPP
- Partial repowering: 1.6 GW of turbines retrofitted in 2021

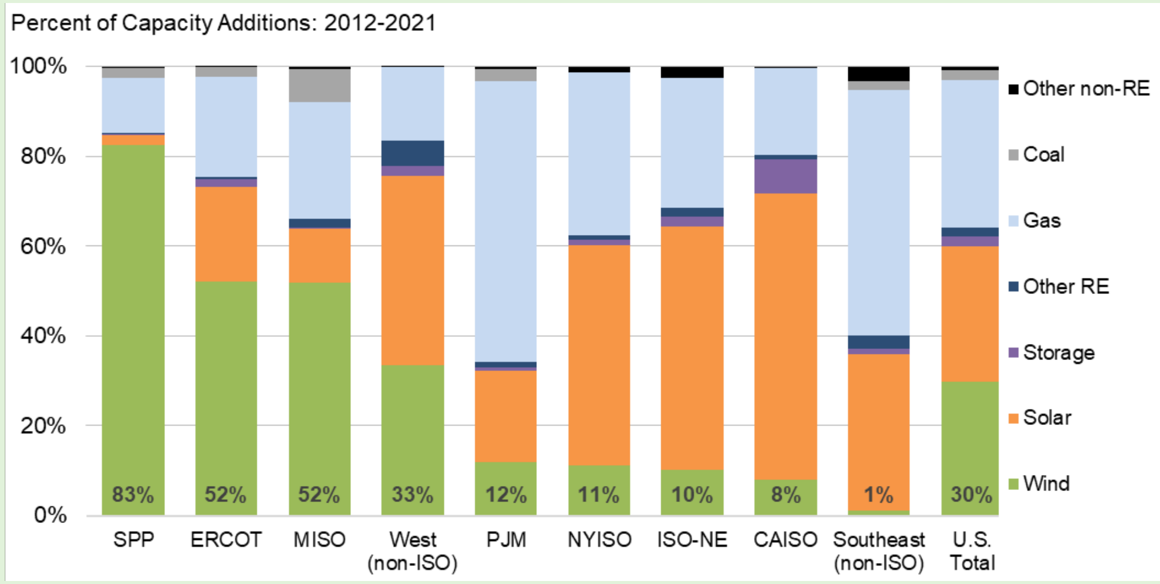
Interactive data visualization: https://emp.lbl.gov/wind-energy-growth

Wind power represented the second largest source of U.S. electric-capacity additions in 2021, at 32%, behind solar's 45%

Relative contribution of resource types in annual capacity additions



Resource capacity additions by region: 2012-2021



Sources: Hitachi, ACP, EIA, Berkeley Lab

Over the last decade, wind has comprised 30% of total capacity additions, and a much higher proportion in SPP, ERCOT, and MISO

Globally, the United States ranked 2nd in annual and cumulative total wind power capacity additions in 2021

Annual Capacity (2021, GW)	
China	47.6
United States	**13.4**
Brazil	3.8
Vietnam	3.5
United Kingdom	2.6
Sweden	2.1
Germany	1.9
Australia	1.7
India	1.5
Turkey	1.4
Rest of World	14.7
TOTAL	**94.3**

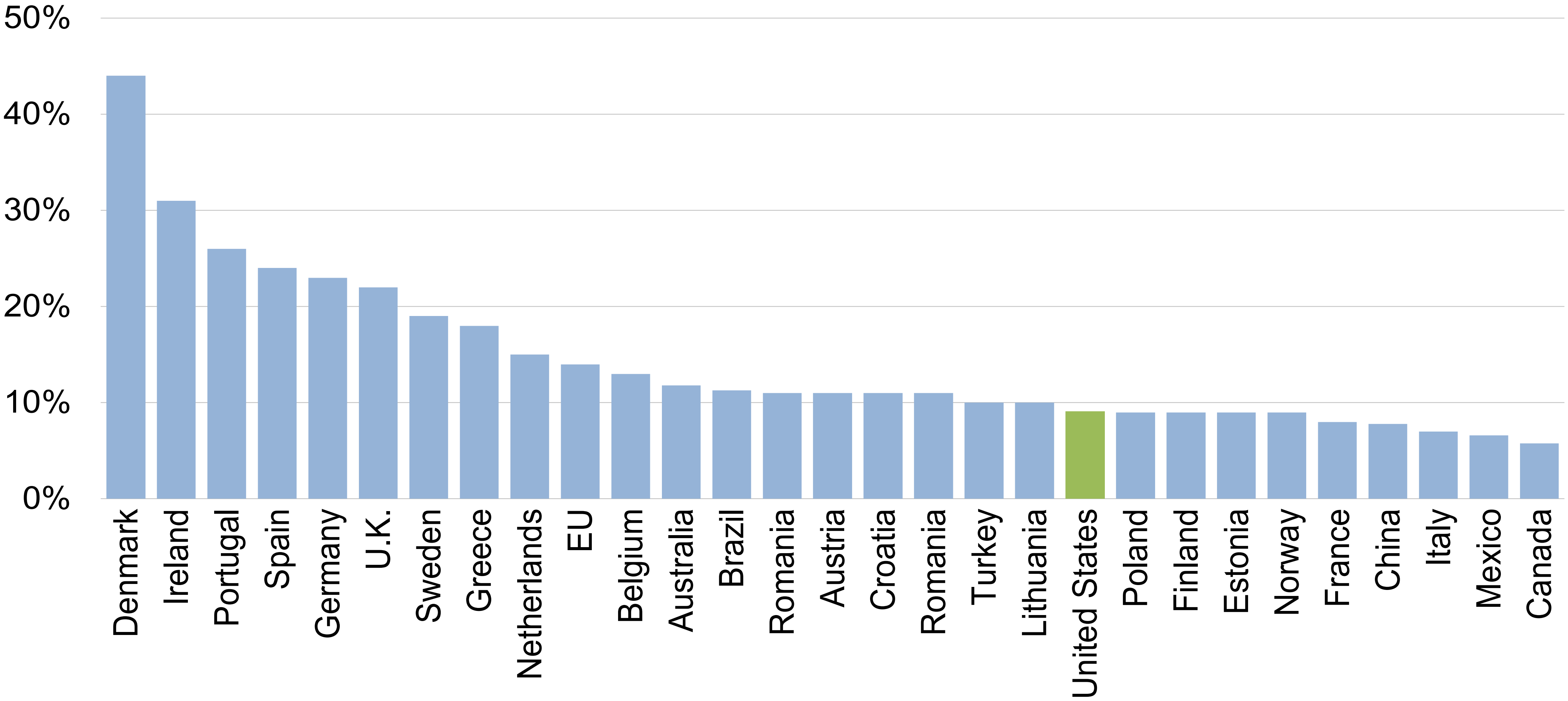
Cumulative Capacity (end of 2021, GW)	
China	338.3
United States	**135.9**
Germany	64.5
India	40.1
Spain	28.3
United Kingdom	26.6
Brazil	21.6
France	19.1
Canada	14.3
Sweden	12.1
Rest of World	138.1
TOTAL	**838.9**

Sources: GWEC, ACP

- Global wind additions totaled over 94 GW of newly added capacity
- U.S. remains a distant second to China in annual and cumulative capacity

The United States ranks lower than many other countries in terms of wind energy as a share of total generation

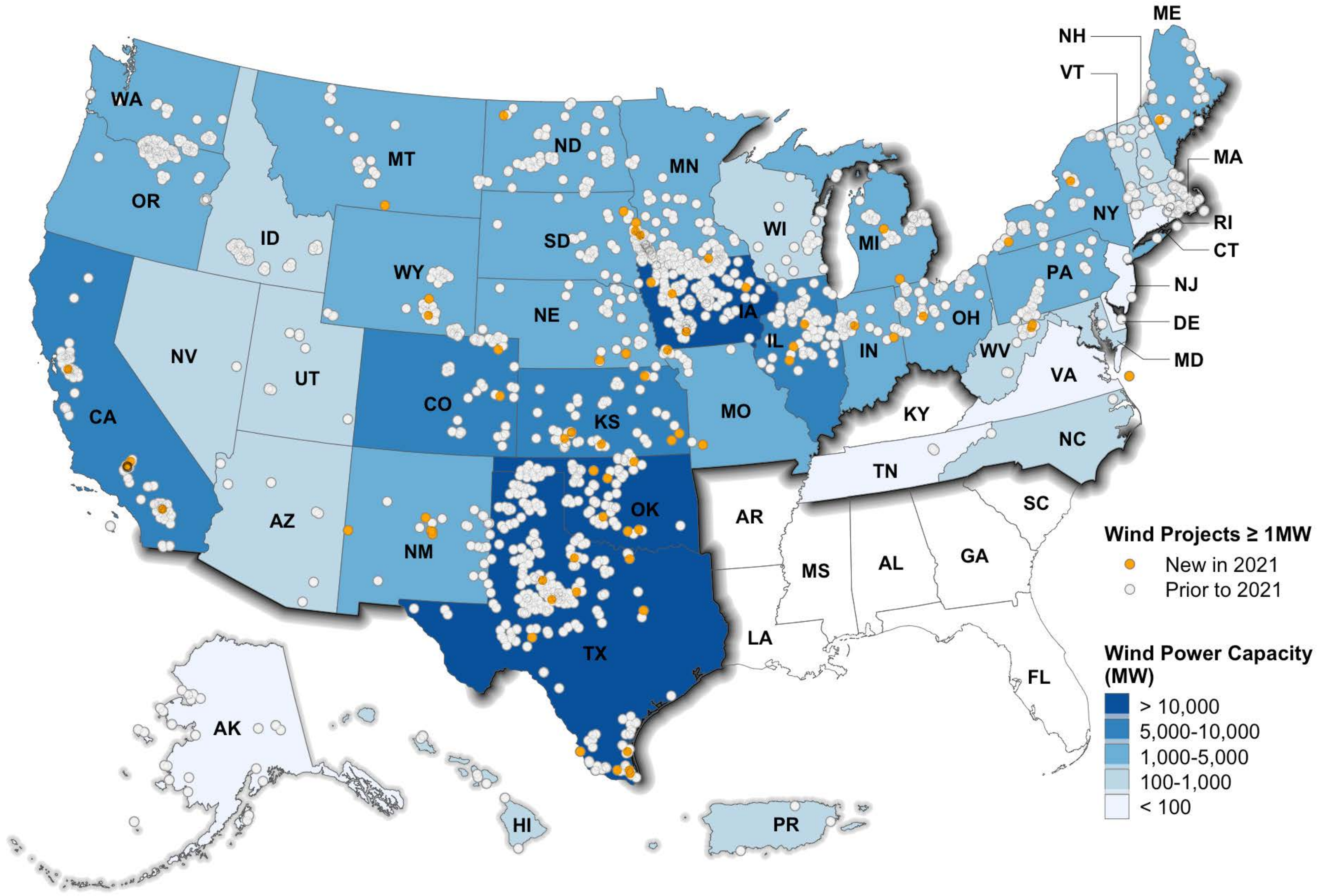
Wind as Percentage of Total Generation in 2021



Source: ACP

Note: Figure includes a subset of the top global wind markets

The geographic spread of wind power projects across the United States is broad, with the exception of the Southeast



Interactive data visualization:
https://emp.lbl.gov/wind-energy-growth

Source: ACP, Berkeley Lab

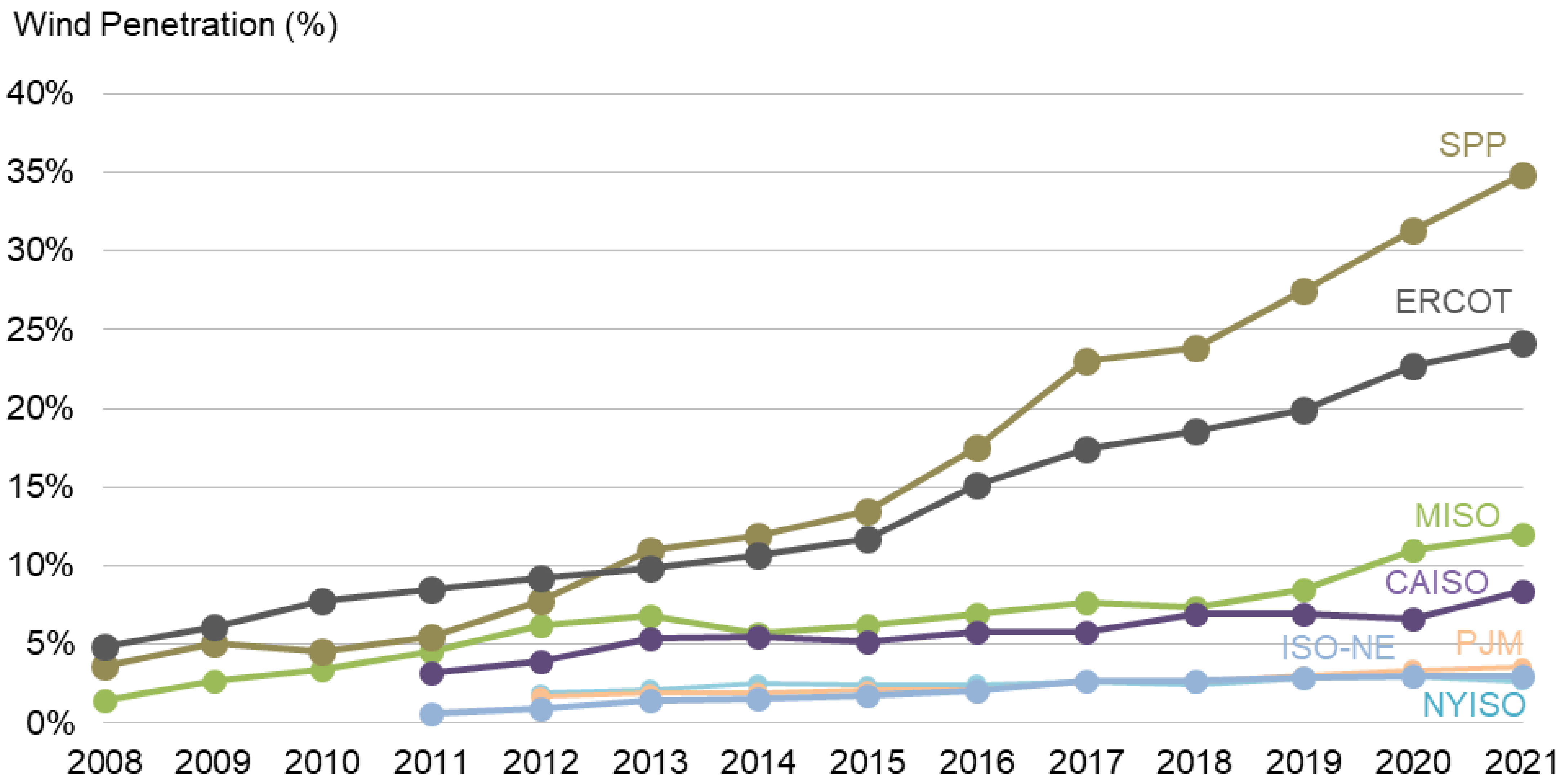
Texas installed the most wind power capacity in 2021; 11 states exceeded 20% wind as a fraction of in-state generation

Installed Capacity (MW)				2021 Wind Generation as a Percentage of:			
Annual (2021)		Cumulative (end of 2021)		In-State Generation		In-State Sales	
Texas	3,343	Texas	35,969	Iowa	55.1%	South Dakota	71.6%
Oklahoma	1,403	Iowa	12,219	South Dakota	52.3%	Iowa	69.1%
New Mexico	1,368	Oklahoma	10,994	Kansas	45.1%	North Dakota	63.3%
Kansas	1,228	Kansas	8,245	Oklahoma	41.4%	Kansas	63.0%
South Dakota	610	Illinois	6,997	North Dakota	34.0%	Wyoming	53.3%
Iowa	600	California	6,142	New Mexico	29.8%	Oklahoma	51.5%
Illinois	580	Colorado	5,035	Colorado	26.0%	New Mexico	41.4%
Michigan	550	Minnesota	4,591	Nebraska	25.1%	Nebraska	30.5%
Indiana	500	North Dakota	4,302	Maine	23.0%	Colorado	26.4%
Missouri	448	New Mexico	4,001	Minnesota	21.6%	Texas	23.5%
Nebraska	388	Oregon	3,842	Texas	20.6%	Maine	22.2%
Wyoming	349	Indiana	3,468	Wyoming	19.3%	Minnesota	19.6%
Colorado	305	Washington	3,396	Oregon	15.6%	Montana	18.9%
North Dakota	299	Wyoming	3,178	Idaho	15.6%	Oregon	18.5%
California	288	Michigan	3,159	Vermont	14.5%	Illinois	13.8%
Minnesota	266	Nebraska	2,942	Montana	11.5%	Washington	10.8%
Ohio	247	South Dakota	2,915	Illinois	10.2%	Idaho	10.5%
Montana	240	Missouri	2,435	Washington	8.7%	Missouri	8.4%
New York	205	New York	2,191	Missouri	8.4%	Indiana	7.9%
West Virginia	169	Pennsylvania	1,459	Indiana	8.3%	Michigan	7.9%
Rest of U.S.	*27*	*Rest of U.S.*	*8,405*	*Rest of U.S.*	*1.6%*	*Rest of U.S.*	*1.5%*
TOTAL	**13,413**	**TOTAL**	**135,886**	**TOTAL**	**9.1%**	**TOTAL**	**10.0%**

Source: ACP, EIA

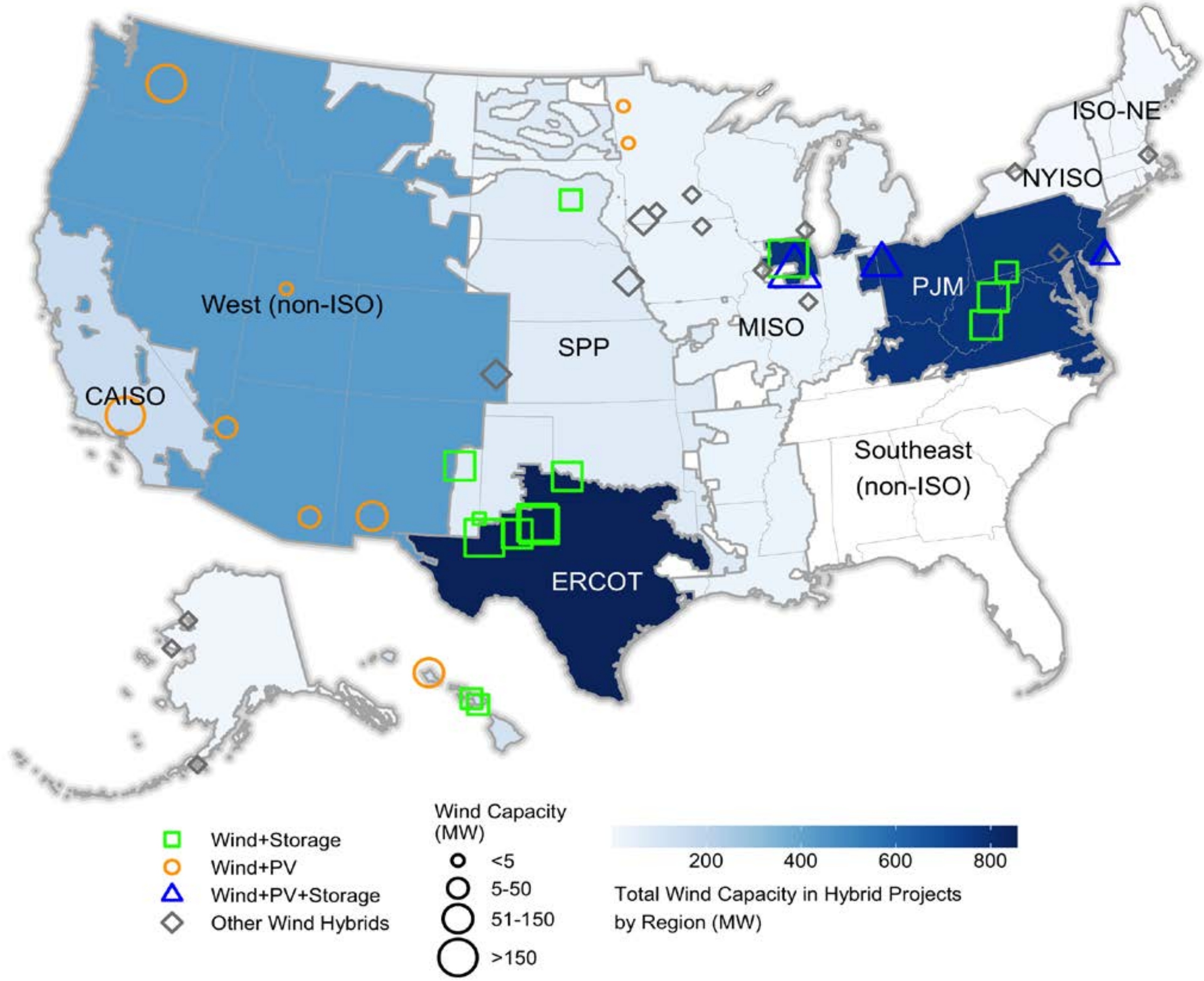
Interactive data visualization: https://emp.lbl.gov/wind-energy-growth

Wind penetration by ISO/RTO is highly variable; in 2021, it was highest in SPP at 35% and ERCOT at 24%



Hybrid wind plants that pair wind with storage, solar, or other resources saw limited growth in 2021; only two new projects

Online Wind Hybrid / Co-located Projects

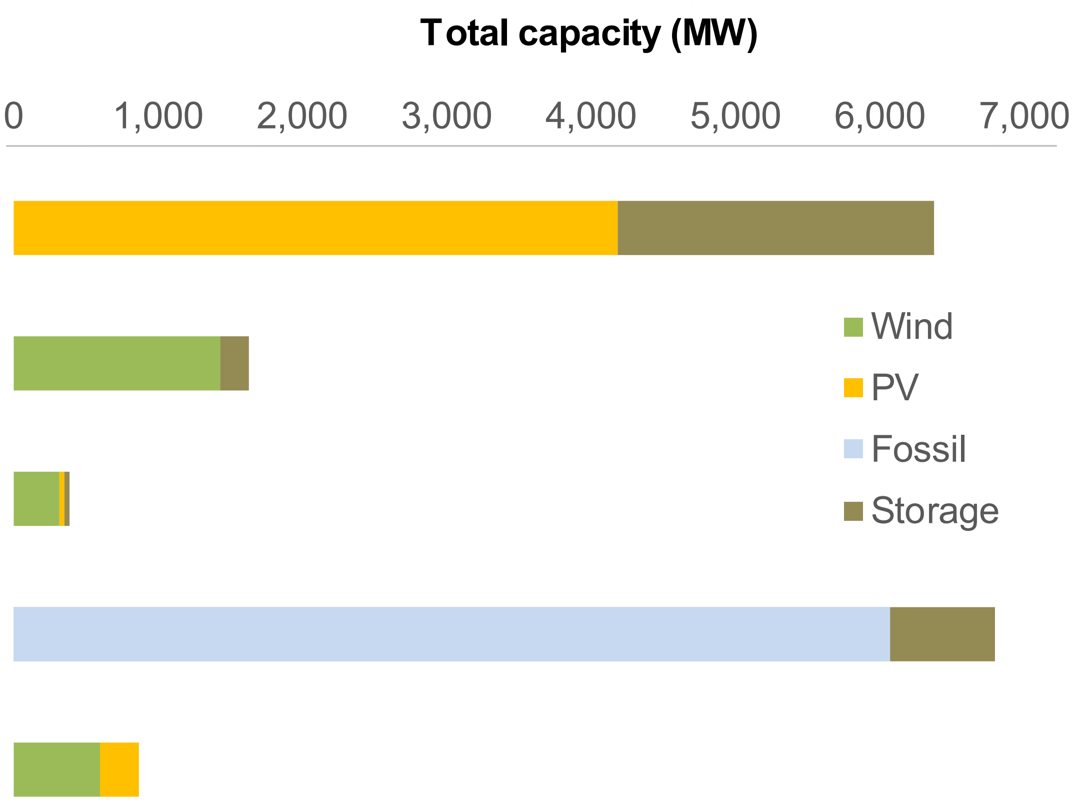


- 41 hybrid wind power plants in operation at the end of 2021
- Represent 2.4 GW of wind power and 0.9 GW of co-located resources
- Most common wind hybrid project combines wind+storage; other combinations include wind+PV; wind+PV+storage; wind+fossil
- ERCOT, PJM, non-ISO West host largest amount of wind hybrid capacity

Interactive data visualization:
https://emp.lbl.gov/online-hybrid-and-energy-storage-projects

Sources: EIA-860 Early Release, Berkeley Lab

Comparing the frequency and design of a subset of the hybrid / co-located project configurations: end of 2021



	# projects	Storage ratio	Duration (hrs)
PV+Storage	140	53%	3.2
Wind+Storage	14	14%	0.6
Wind+PV+Storage	3	11%	0.5
Fossil+Storage	24	12%	1.2
Wind+PV	9	n/a	n/a

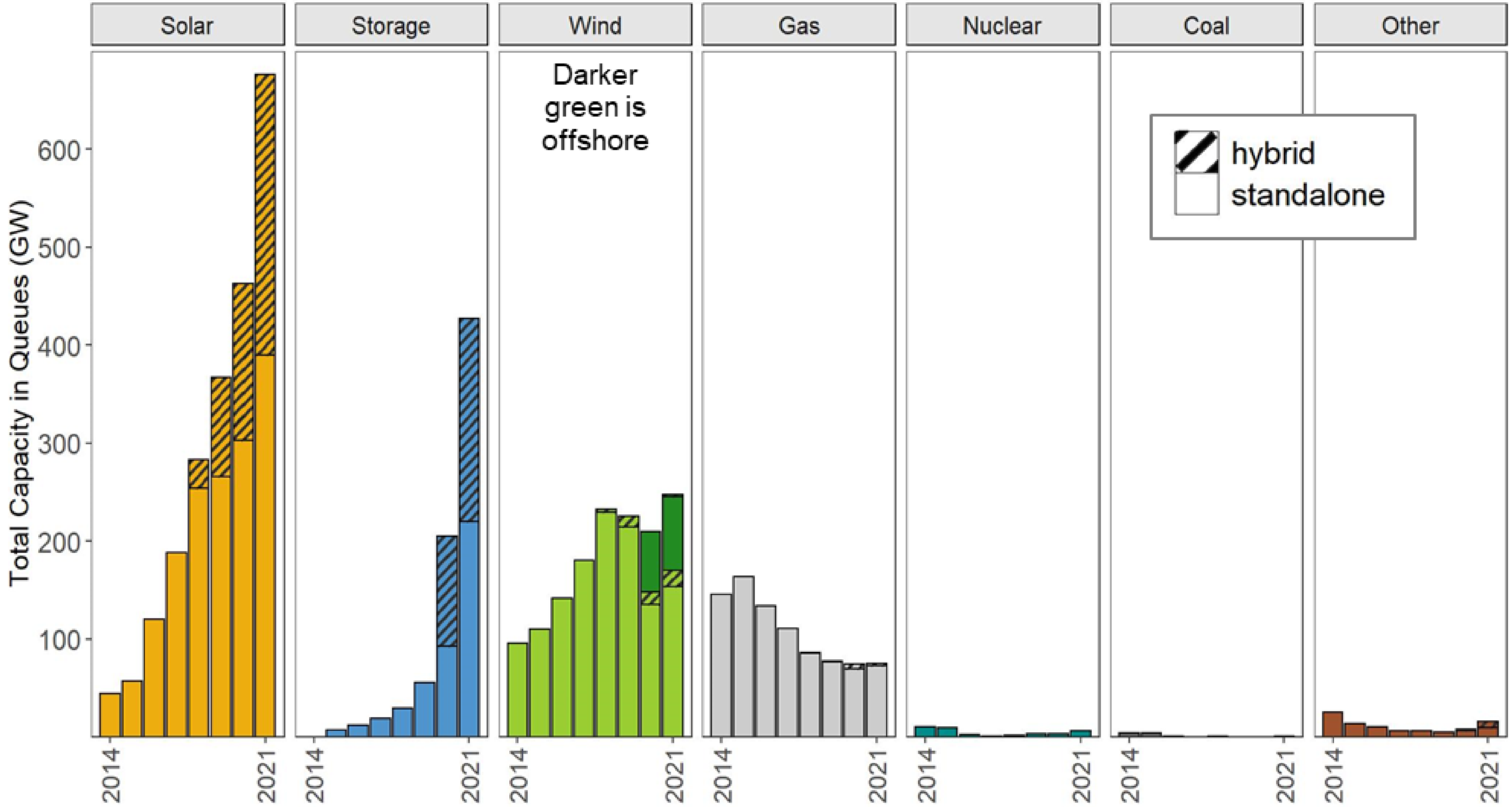
Notes: Not included in the figure are 108 hybrid projects with other configurations. Storage ratio defined as total storage capacity divided by total generator capacity for a given project type.

Sources: EIA 860 Early Release, Berkeley Lab

Most wind hybrids are Wind+Storage, with limited storage duration to serve ancillary services markets

Interactive data visualization: https://emp.lbl.gov/online-hybrid-and-energy-storage-projects

A record 247 GW of wind exists in transmission interconnection queues, but solar and storage are expanding more rapidly



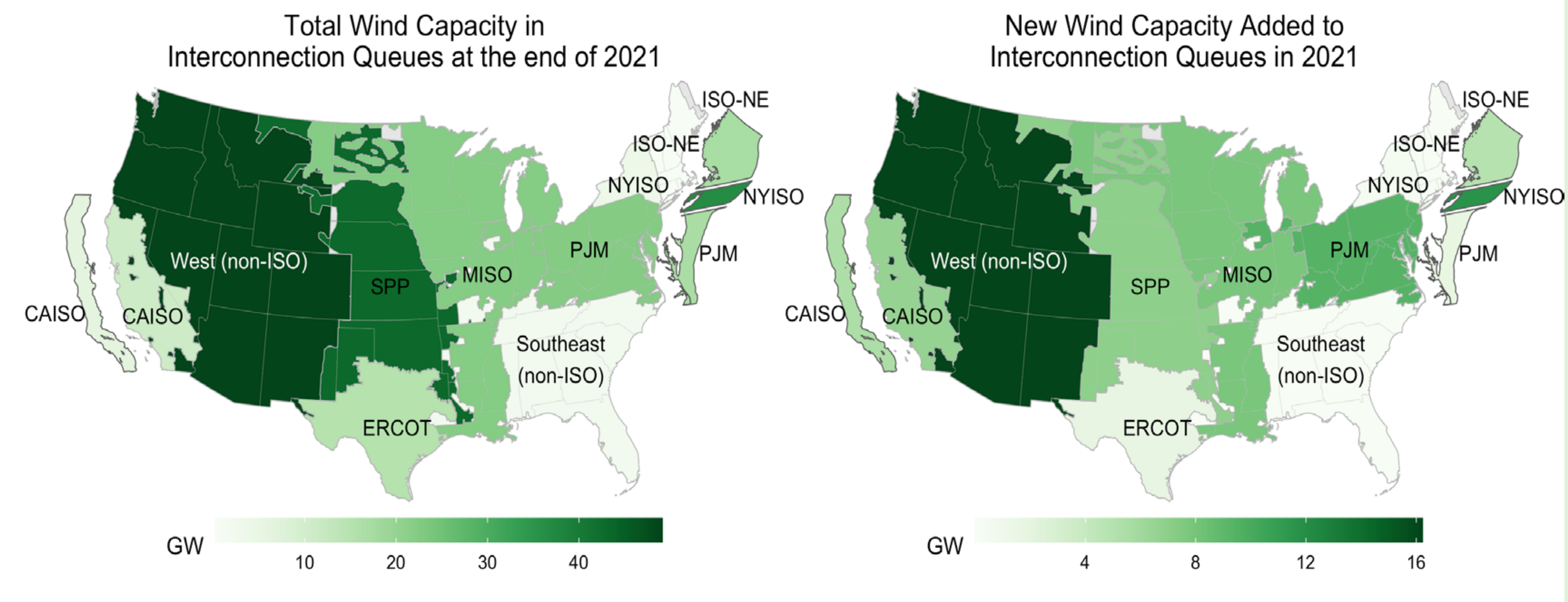
Not all of this capacity will be built: <25% completion rate

Interactive data visualization: https://emp.lbl.gov/generation-storage-and-hybrid-capacity

Note: Storage capacity in hybrids was not estimated for years prior to 2020; offshore wind was not separately identified prior to 2020

Source: Berkeley Lab review of interconnection queues

Larger amounts of wind capacity in non-ISO West, SPP, NYISO, and PJM queues; 31% (77 GW) of wind capacity in queues is offshore

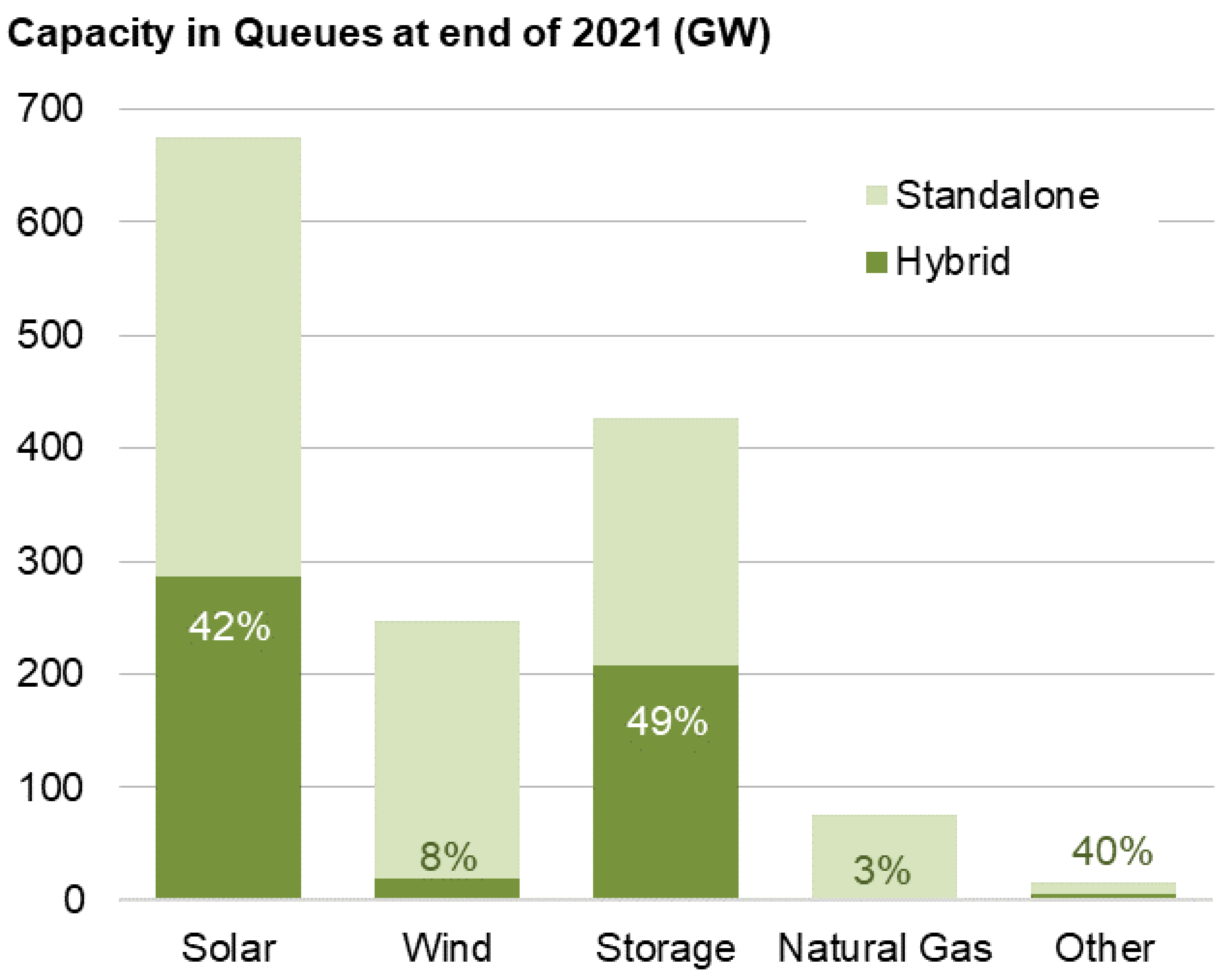


Source: Berkeley Lab review of interconnection queues

Note: Not all of this capacity will be built

Interactive data visualization: https://emp.lbl.gov/generation-storage-and-hybrid-capacity

Interest in hybrid plants has increased: 8% of wind proposed as hybrids (19 GW); larger fraction of 42% of solar proposed as hybrids



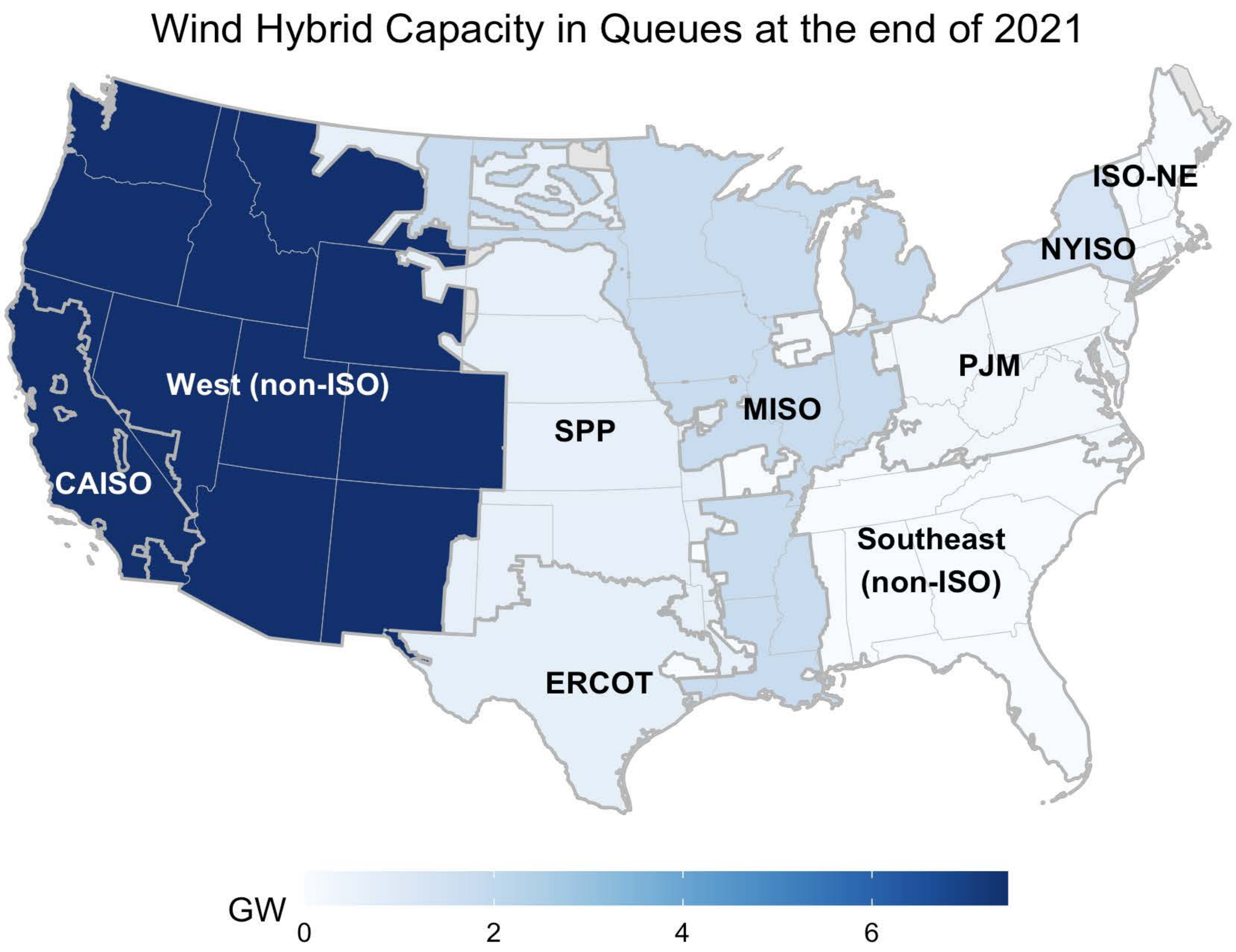
Source: Berkeley Lab review of interconnection queues

Greater commercial interest in solar hybrids is partly due to policy design—the investment tax credit for solar can also be used for paired storage, whereas the production tax credit regularly used by wind plants has no such storage allowance

Notes: (1) Not all of this capacity will be built; (2) Hybrid plants involving multiple generator types (e.g., wind+PV+ storage, wind+PV) show up in all generator categories, presuming the capacity is known for each type.

Interactive data visualization: https://emp.lbl.gov/generation-storage-and-hybrid-capacity

Proposed wind hybrids are primarily located in California and the non-ISO Western regions



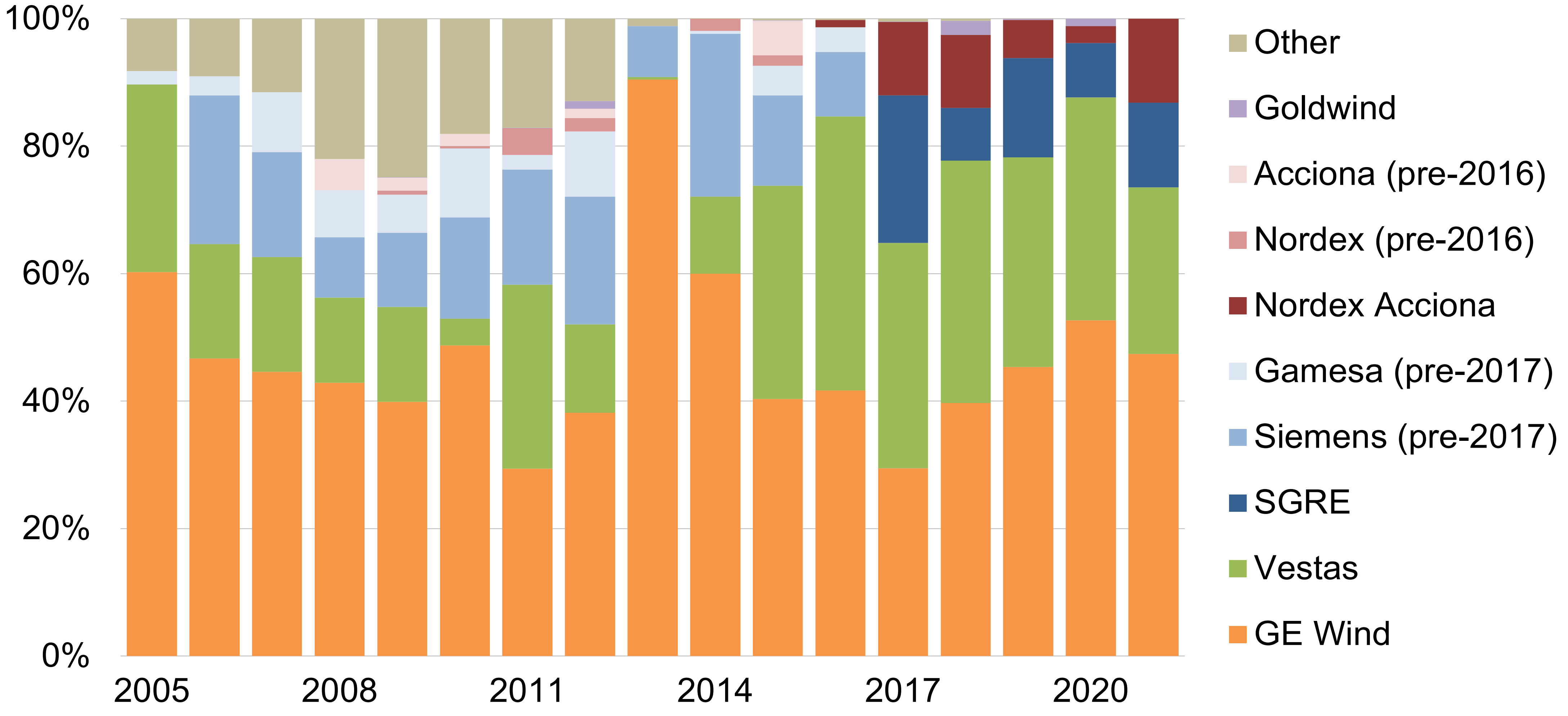
Source: Berkeley Lab review of interconnection queues

Interactive data visualization: https://emp.lbl.gov/generation-storage-and-hybrid-capacity

Industry Trends

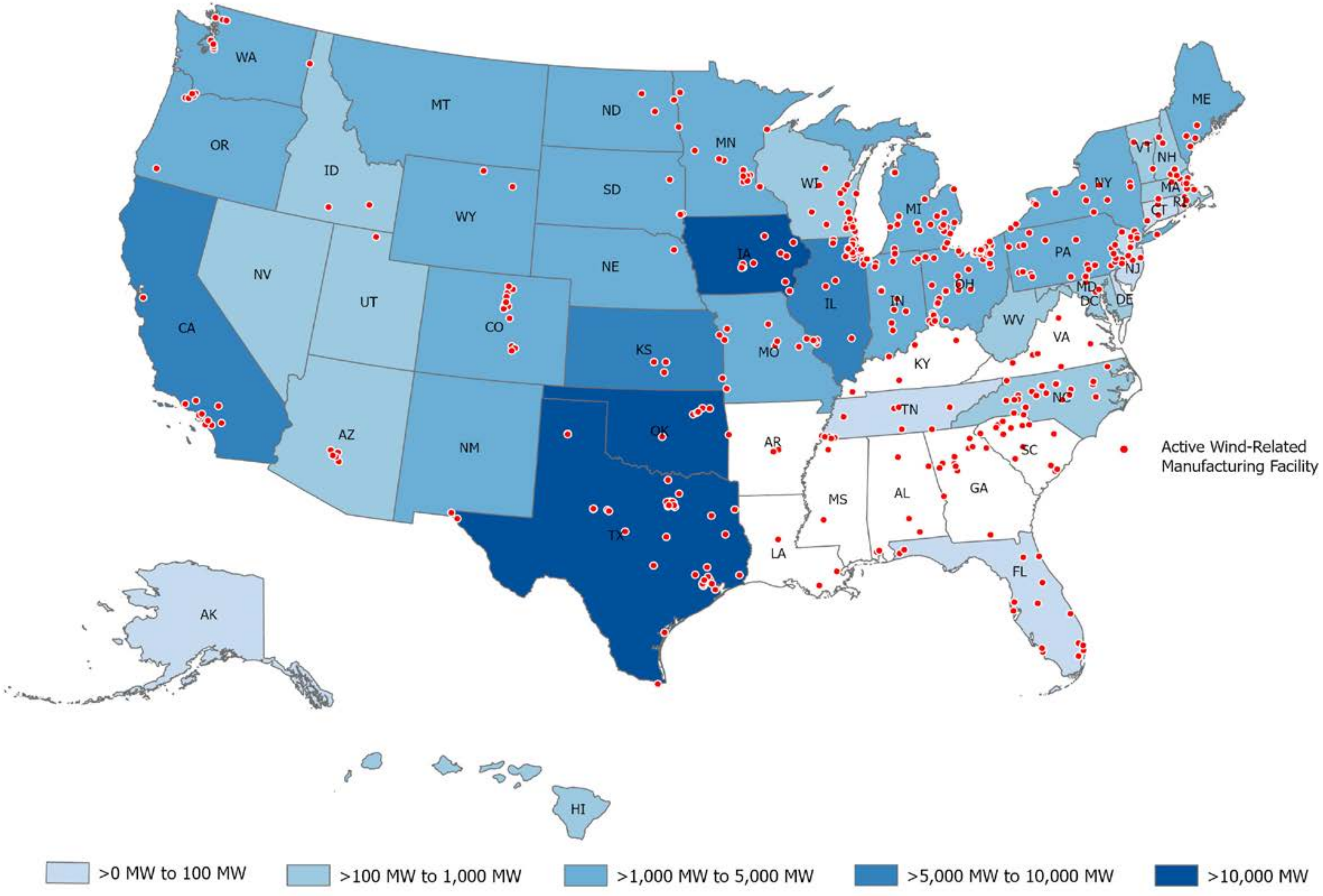
Four turbine manufacturers, led by GE, supplied all of the U.S. wind power capacity installed in 2021

U.S. Market Share by MW



Source: ACP

The domestic supply chain for wind equipment is diverse, with manufacturing facilities located in all regions of the country

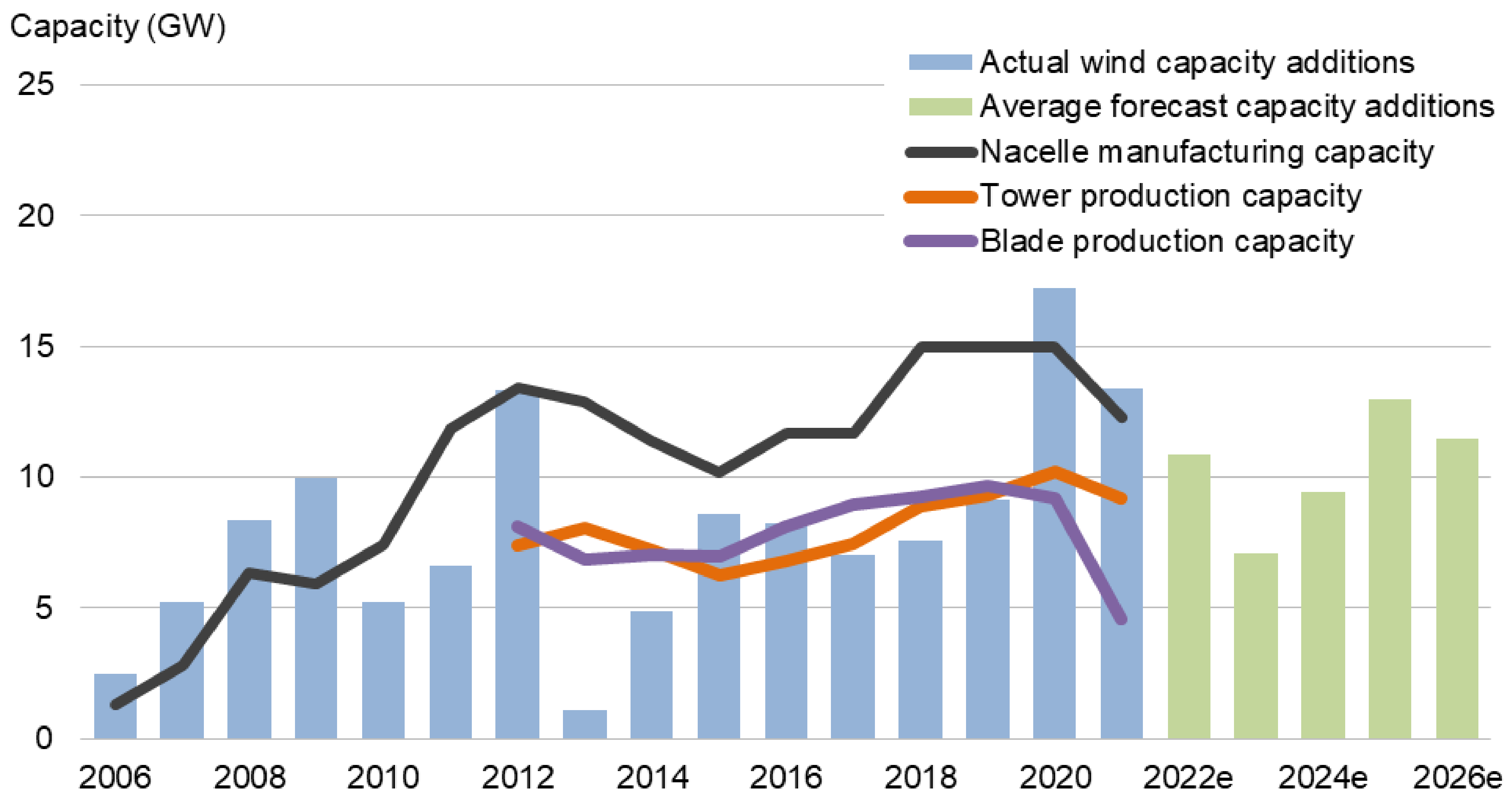


Wind-related job totals in the United States increased by 2.9% in 2021, 120,164 full-time workers

These jobs include, among others, those in construction (43,371) and manufacturing (23,644)

Source: ACP

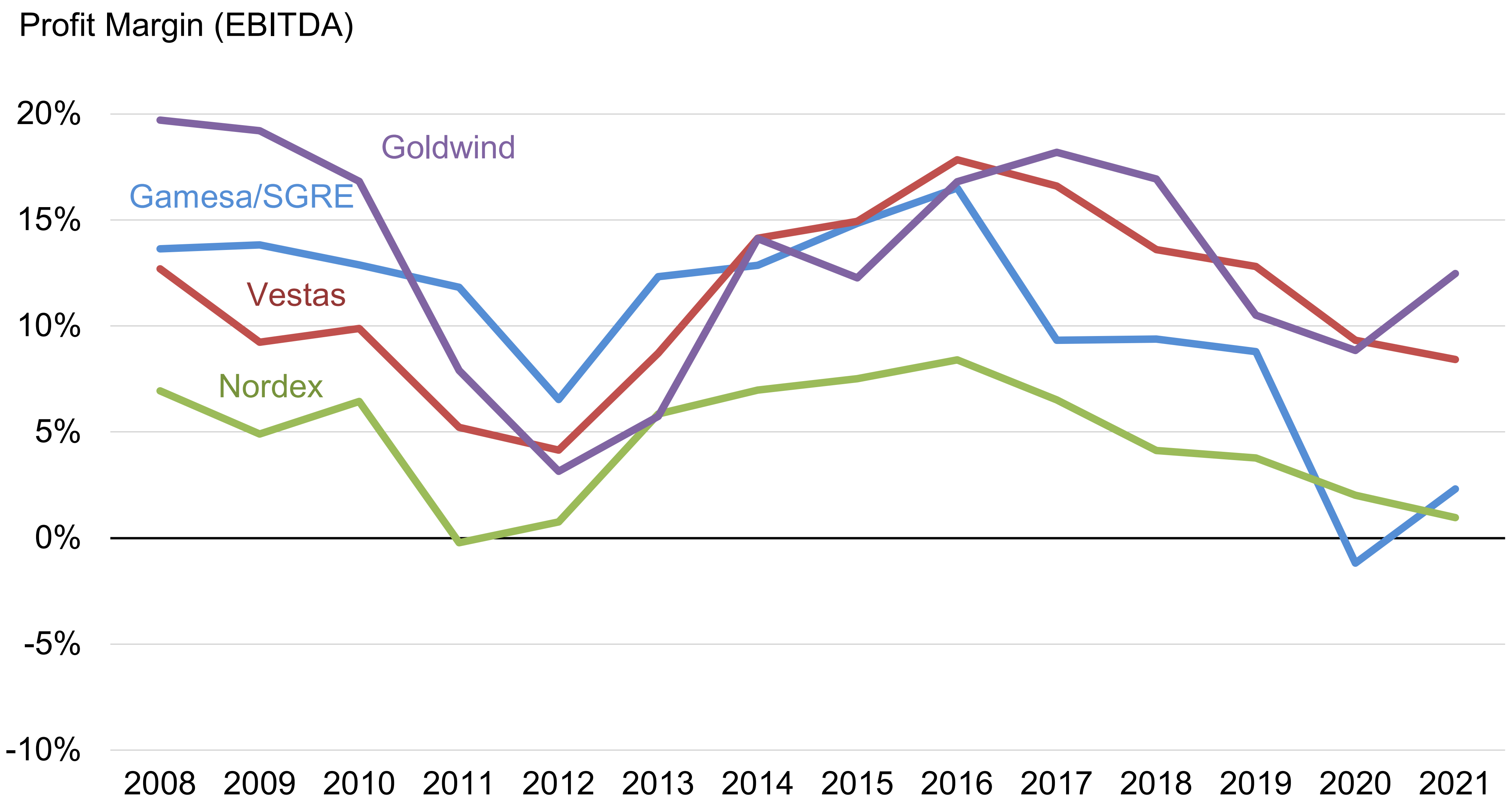
The domestic wind industry supply chain contracted in 2021, with a 50% decline in blade manufacturing as three facilities closed



Sources: ACP, independent analyst projections, Berkeley Lab

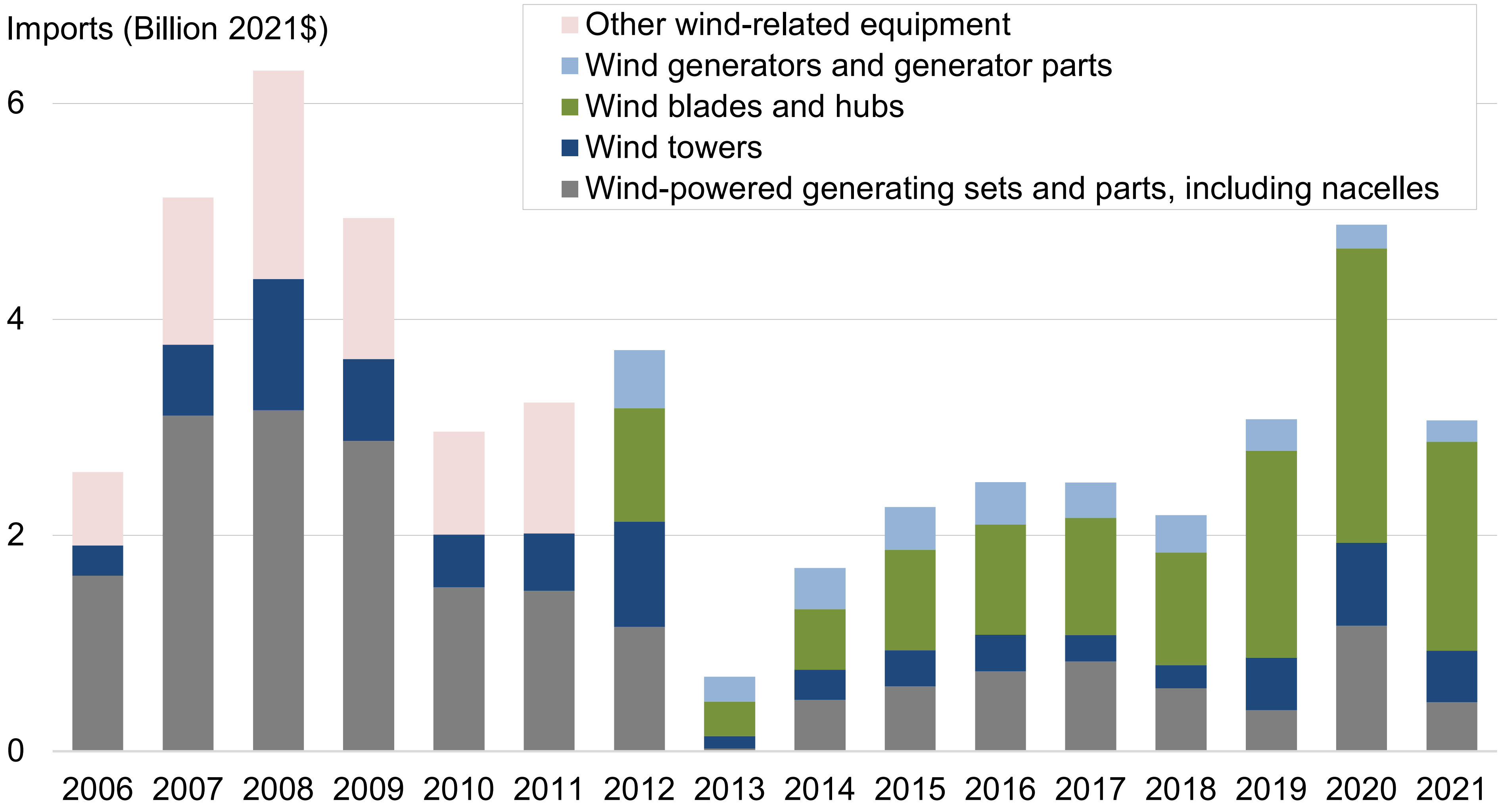
Note: Actual nacelle assembly, tower production, and blades production would be expected to be below maximum production capacity.

The profitability of global wind turbine manufacturers has generally declined over the last several years



Sources: OEM annual reports and financial statements

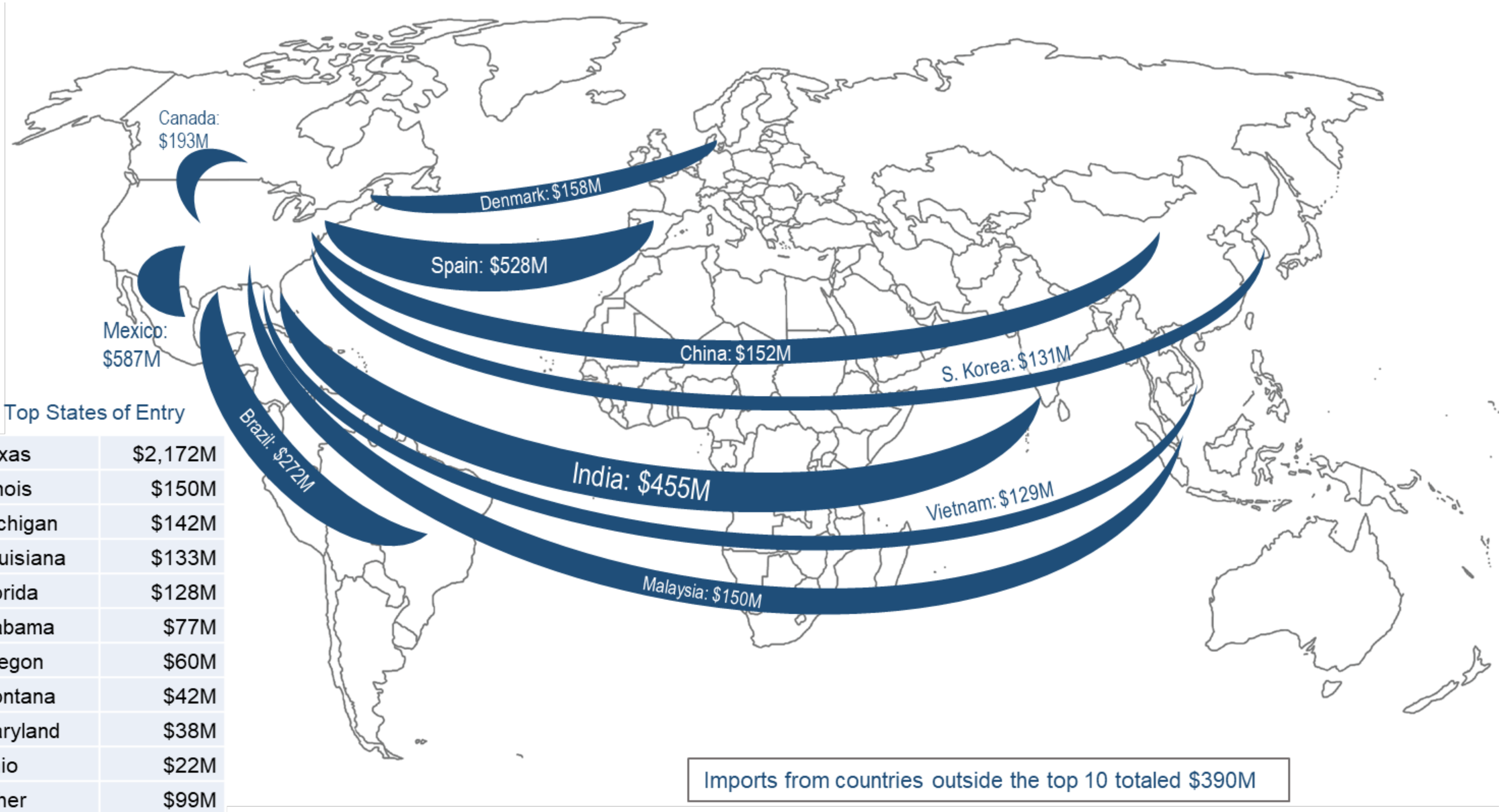
Imports of wind equipment into the United States are sizable, at $3.1 billion in 2021



Source: Berkeley Lab analysis of data from USA Trade Online, https://usatrade.census.gov

Notes: Figure only includes tracked trade categories, misses other wind-related imports; wind-related trade codes and definitions are not consistent over the full time period; see full report for the assumptions used to generate the figure.

Tracked wind equipment imports into the United States in 2021 came from multiple regions of the world



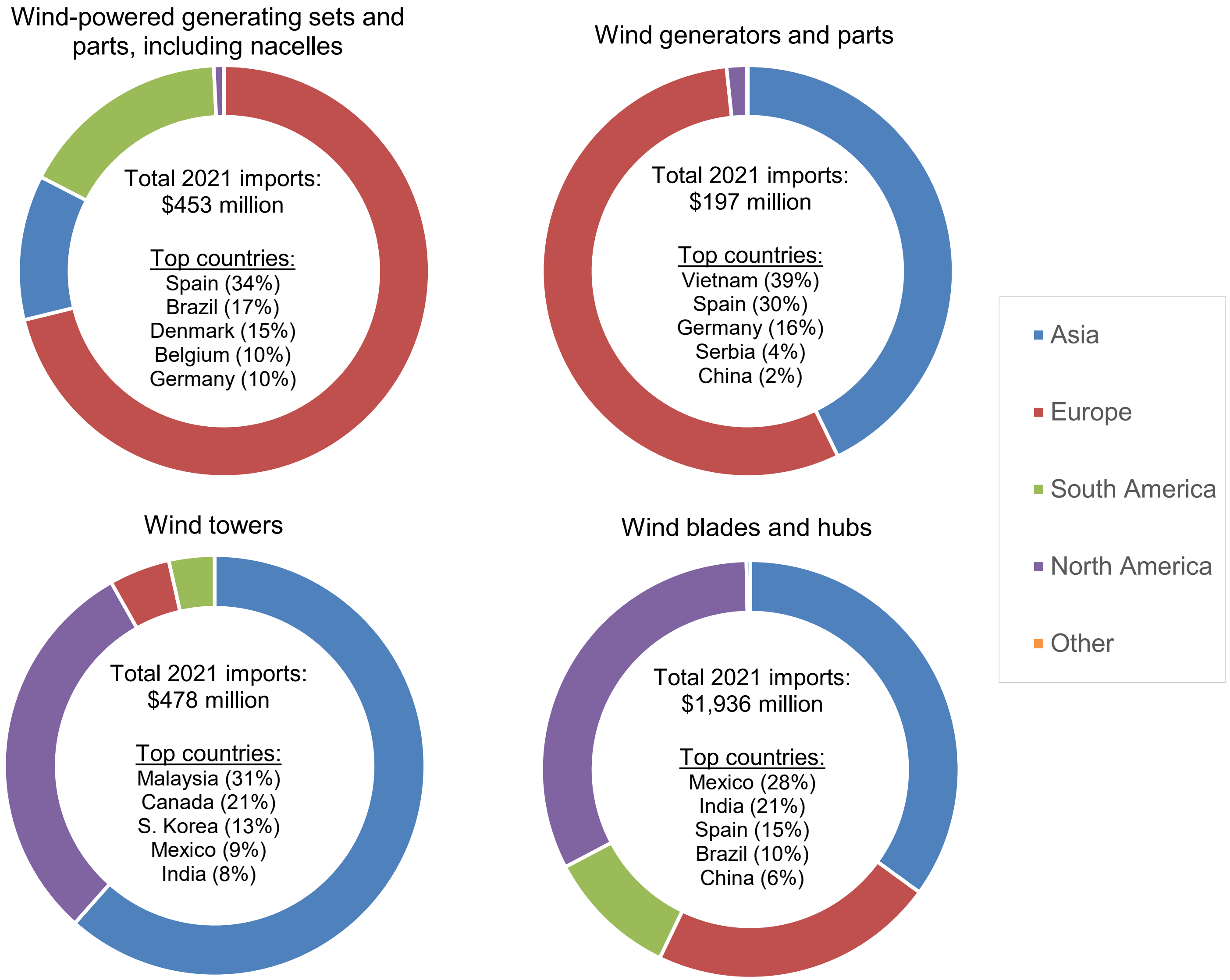
Top States of Entry

Texas	$2,172M
Illinois	$150M
Michigan	$142M
Louisiana	$133M
Florida	$128M
Alabama	$77M
Oregon	$60M
Montana	$42M
Maryland	$38M
Ohio	$22M
Other	$99M

Source: Berkeley Lab analysis of data from USA Trade Online, https://usatrade.census.gov

Notes: Line widths are proportional to amount of imports, by country. Figure does not intend to depict the destination of these imports, by state. Tracked wind-specific equipment includes: wind-powered generating sets and parts, towers, generators and generator parts, blades and hubs, and nacelles

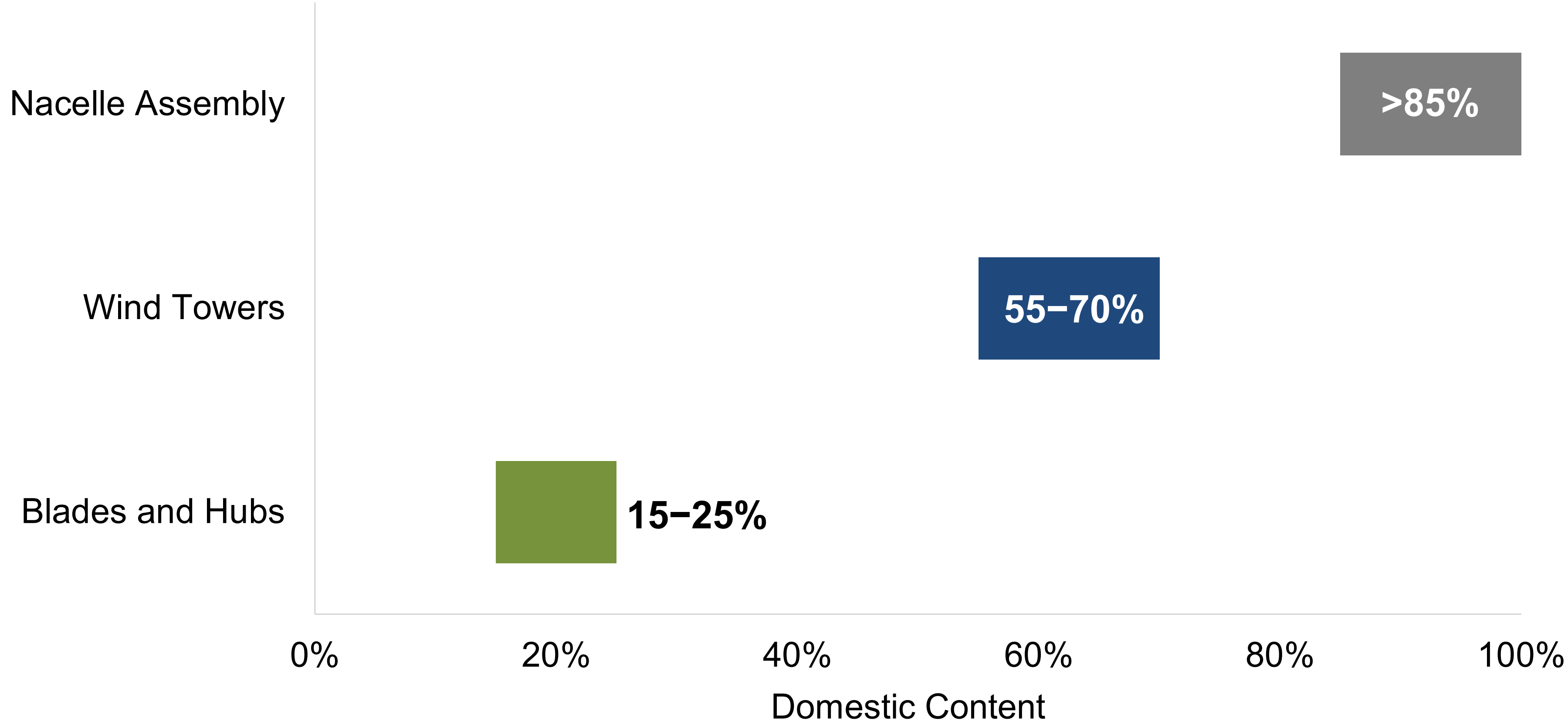
Source markets for 2021 wind equipment imports vary by type of wind equipment



- Spain, followed by Brazil, Denmark, Belgium, and Germany, were the primary source countries for wind-powered generating sets and parts, including nacelles, in 2021
- Tower imports came from a mix of countries near and far—Malaysia, Canada, South Korea, Mexico, and India
- With regard to blades and hubs, Mexico and India accounted for almost 50% of imports, with Spain, Brazil, and China the next largest source countries
- Over two thirds of wind-related generators and generator parts came from Vietnam and Spain, the rest primarily from Germany, Serbia, and China

Source: Berkeley Lab analysis of data from USA Trade Online, https://usatrade.census.gov

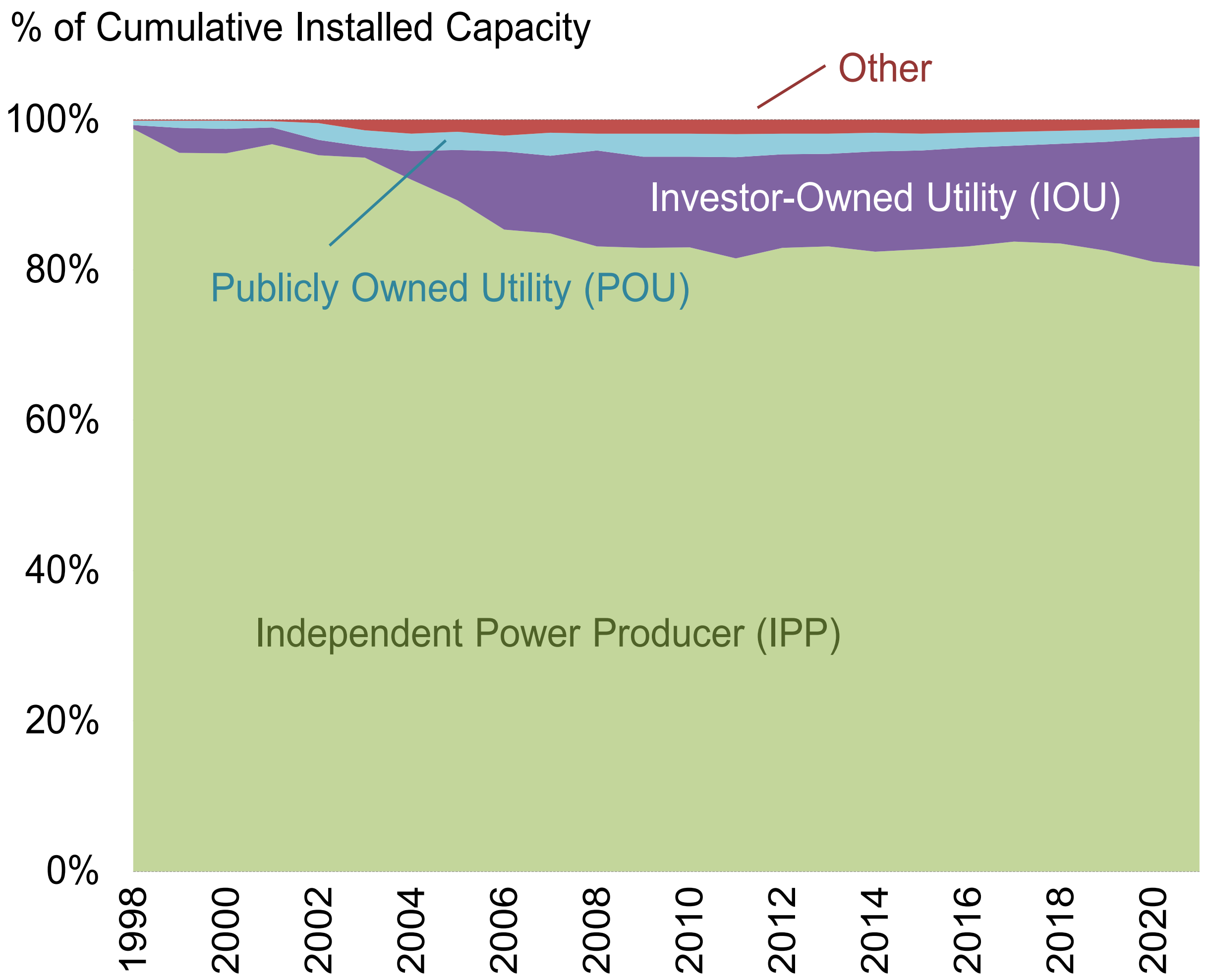
Domestic manufacturing content in 2021 was relatively strong for nacelle assembly and towers, with blade production declining rapidly

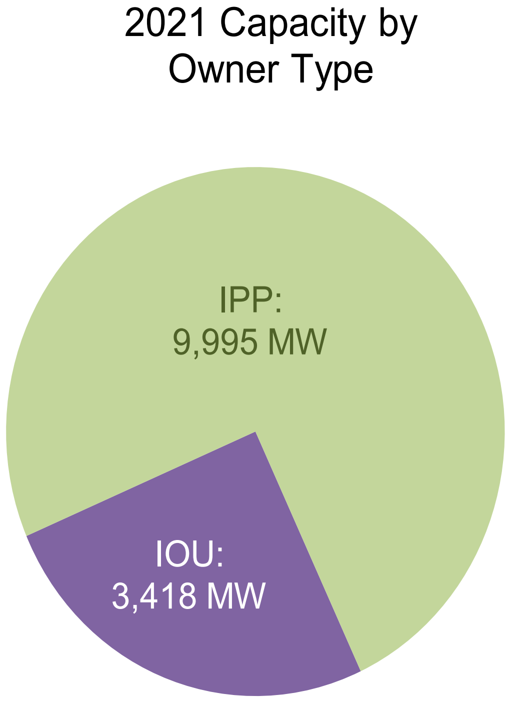


Source: Berkeley Lab

Imports occur in untracked trade categories not included above, including many nacelle internals. Blade domestic content has declined in recent years. BloombergNEF (2021) has recently estimated that a typical onshore wind project in the U.S. sources 57% of its components (by dollar value) domestically.

Independent Power Producers own the majority of wind assets built in 2021, but Investor-Owned Utilities own a sizable share

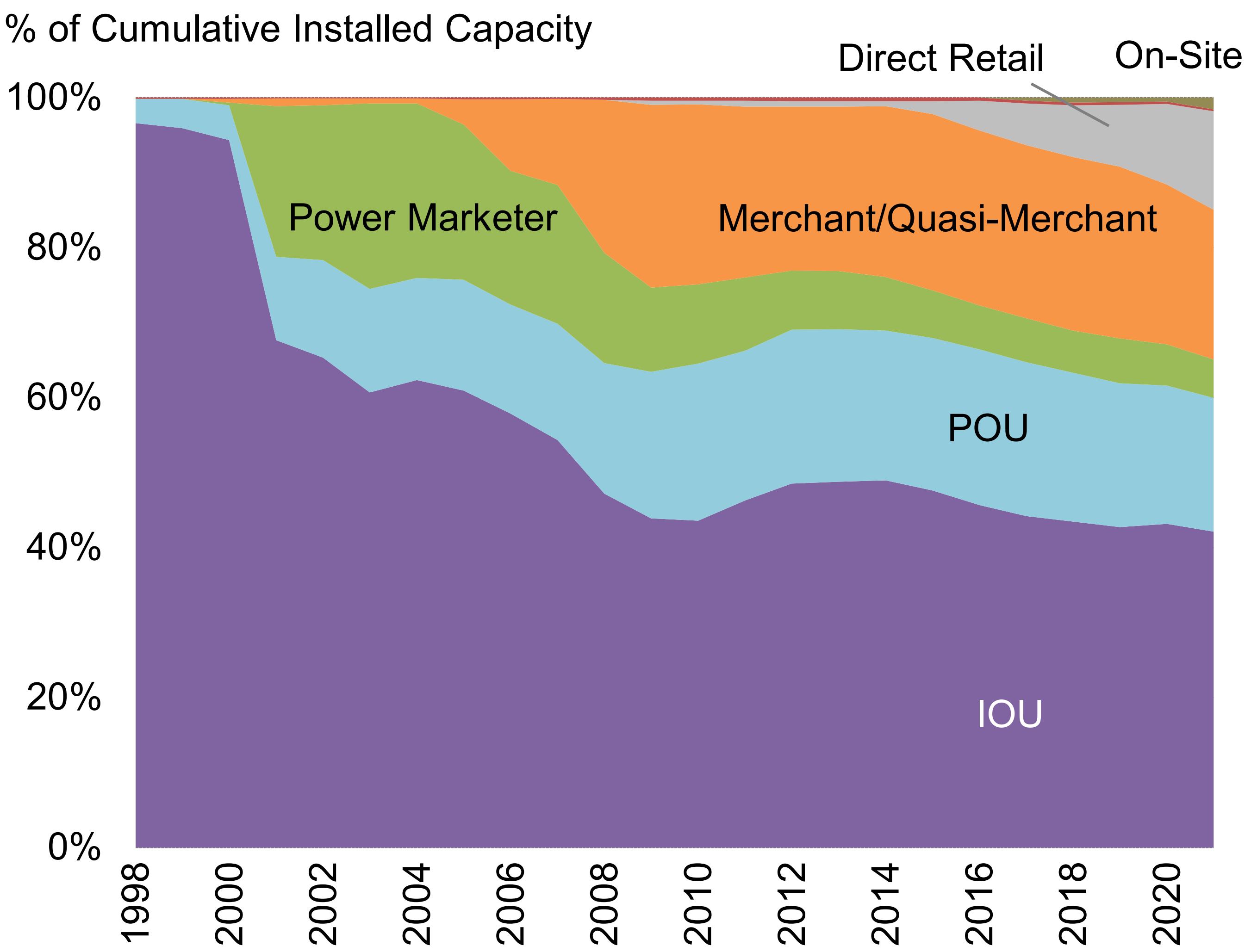


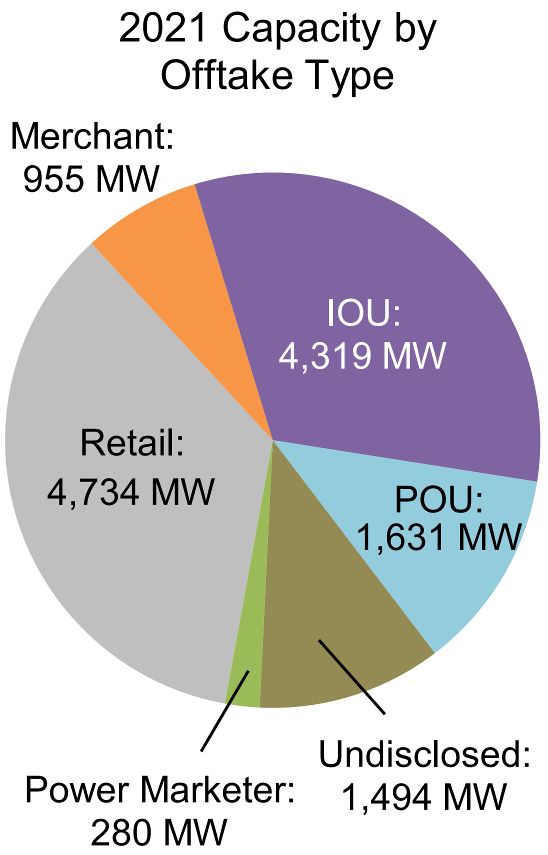


Source: Berkeley Lab estimates based on ACP

Note: Graphic on left shows distribution among growing cumulative fleet of projects installed. Pie chart shows distribution only among those projects built in 2021.

Direct retail sales and merchant wind projects, in combination, matched or surpassed long-term contracted sales to utilities in 2021



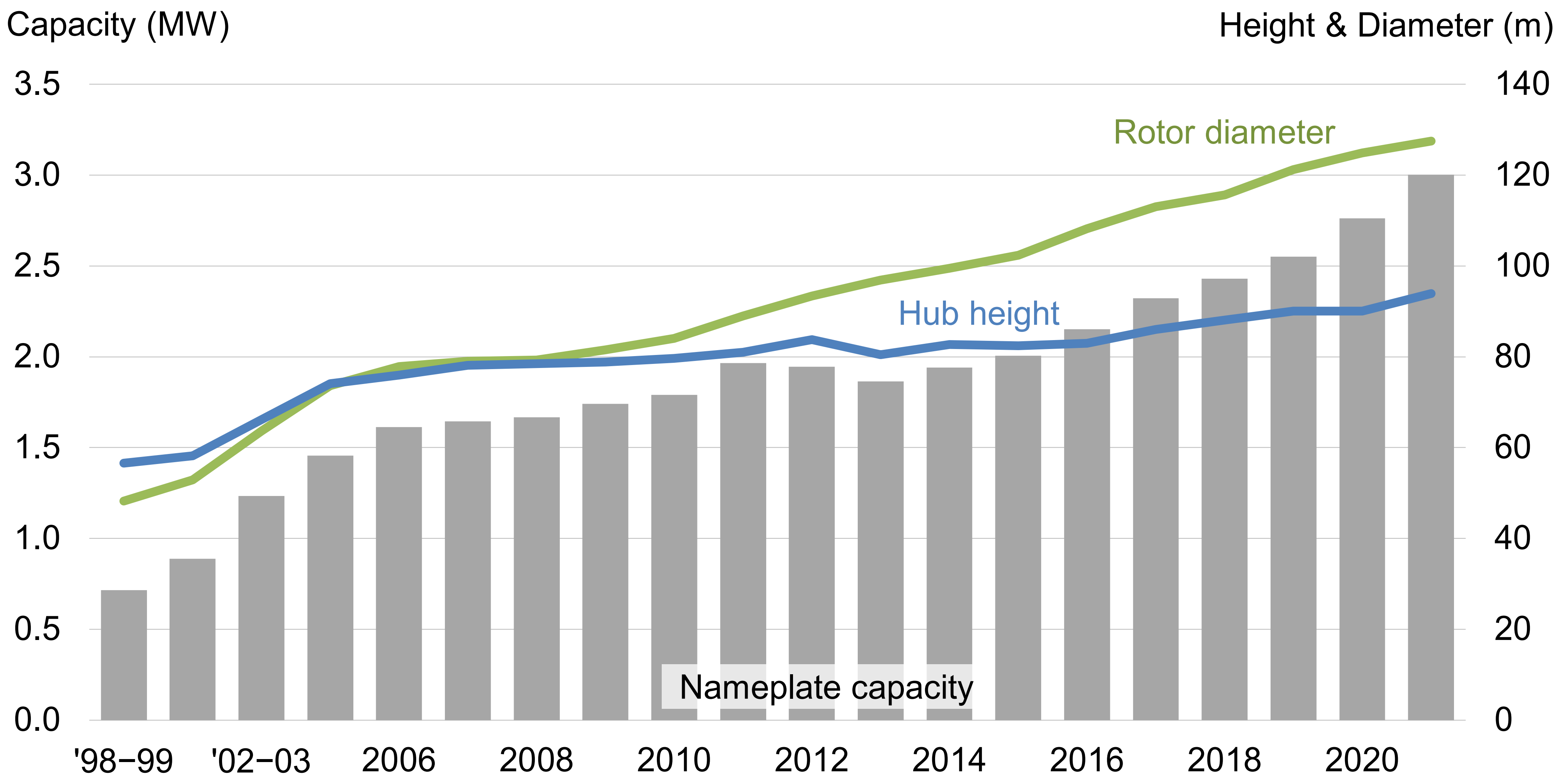


Source: Berkeley Lab estimates based on ACP

Note: Graphic on left shows distribution among growing cumulative fleet of projects installed. Pie chart shows distribution only among those projects built in 2021.

Technology Trends

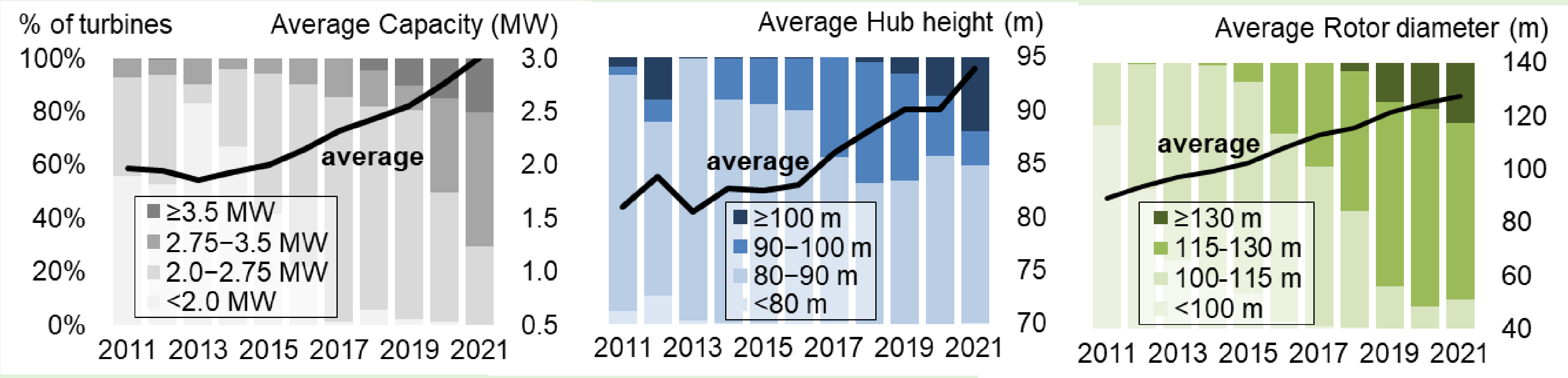
Turbine capacity, rotor diameter, and hub height have all increased significantly over the long term



Sources: ACP, Berkeley Lab

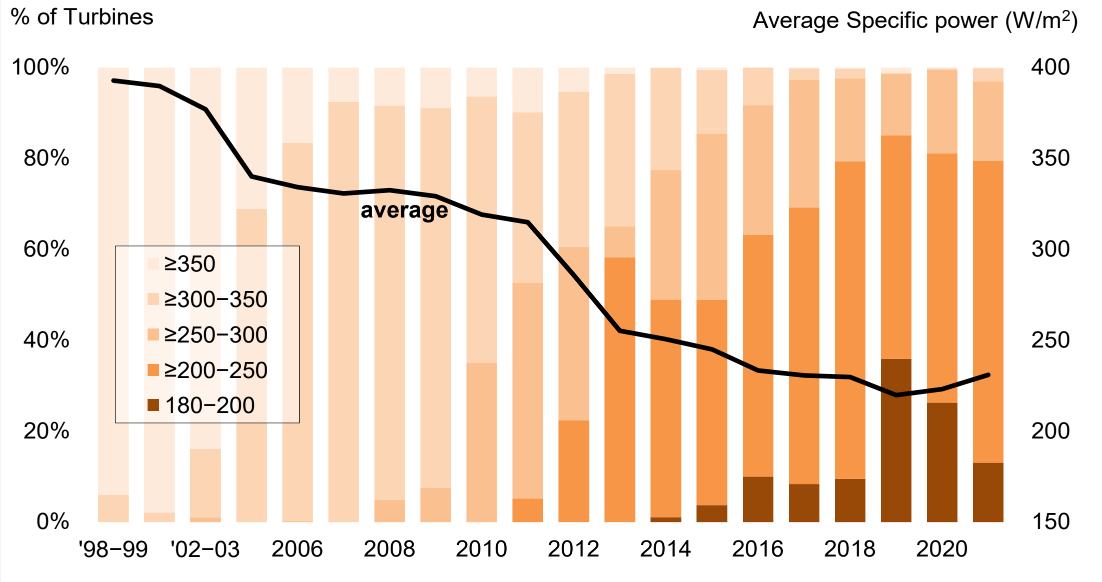
Interactive data visualization: https://emp.lbl.gov/wind-power-technology-trends

Turbine size maintains upward trajectory; turbines originally designed for lower wind speeds dominate the market



Specific power: turbine capacity divided by swept rotor area; lower specific power leads to higher capacity factors, as shown later

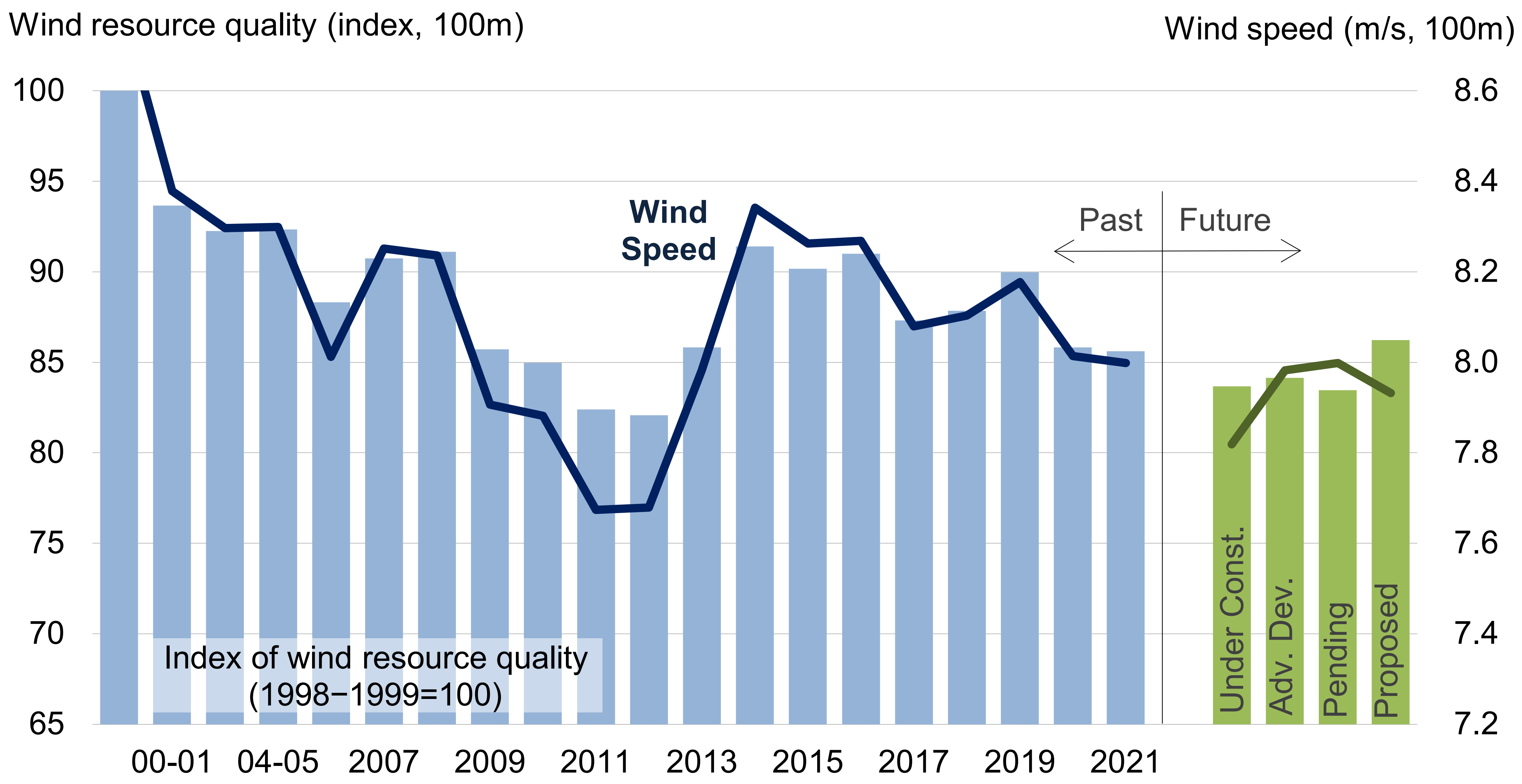
2021 average = 231 W/m^2



Sources: ACP, Berkeley Lab

Interactive data visualization: https://emp.lbl.gov/specific-power

Wind turbines were deployed in somewhat lower wind-speed sites in 2021 than in the previous seven years

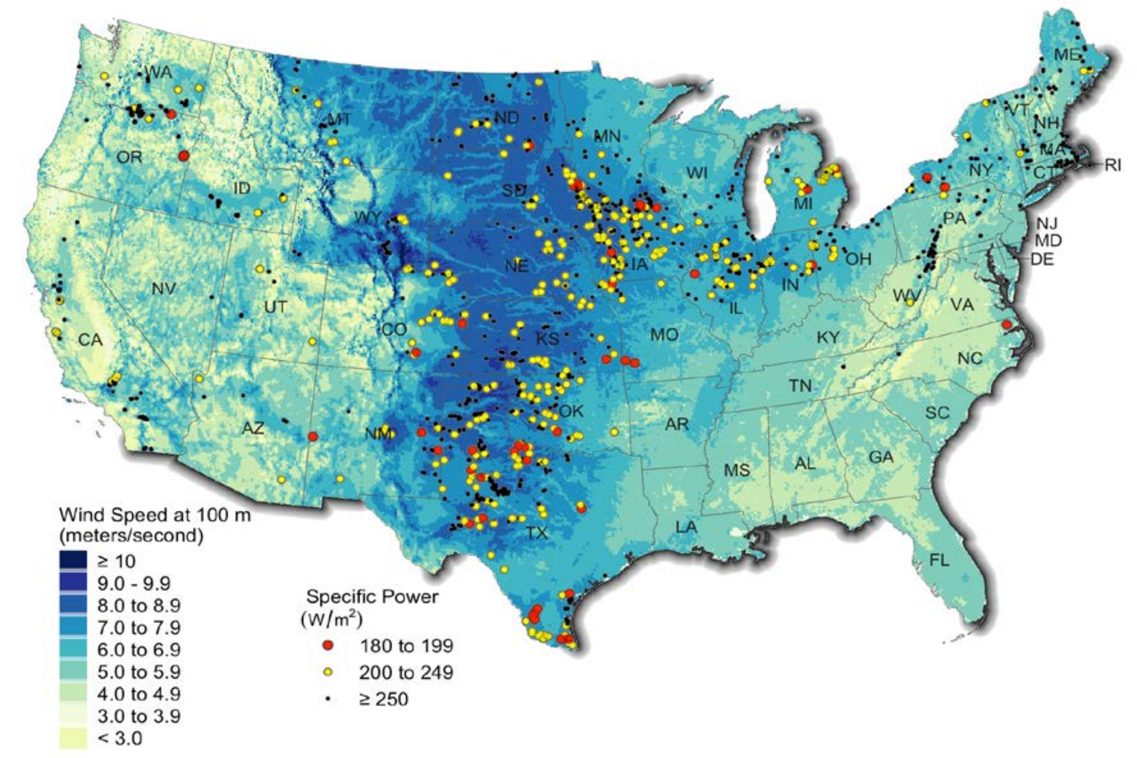


Sources: ACP, Berkeley Lab, AWS Truepower, FAA files

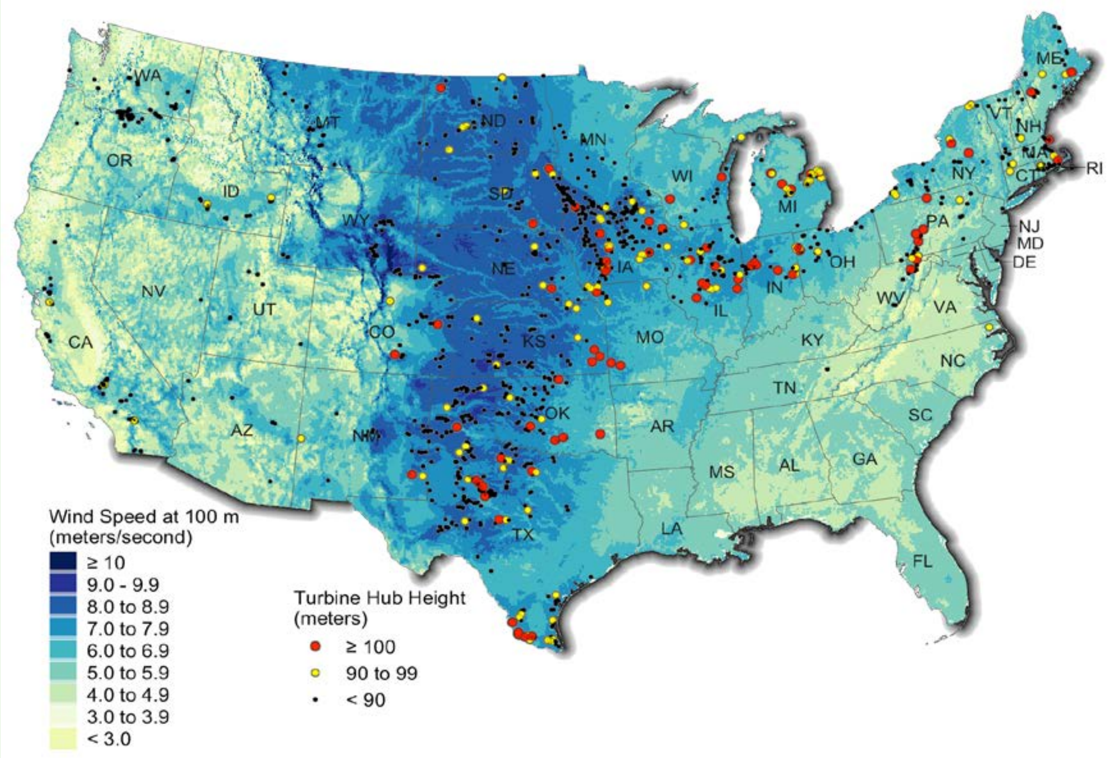
Note: Wind resource quality index is based on site estimates of gross capacity factor at 100 meters by AWS Truepower. A single, common wind-turbine power curve is used across all sites and timeframes, and no losses are assumed. Values are indexed to those projects built in 1998—1999.

Low specific power turbines are deployed on widespread basis; taller towers are seeing increased use in wider variety of sites

Specific Power



Hub Height

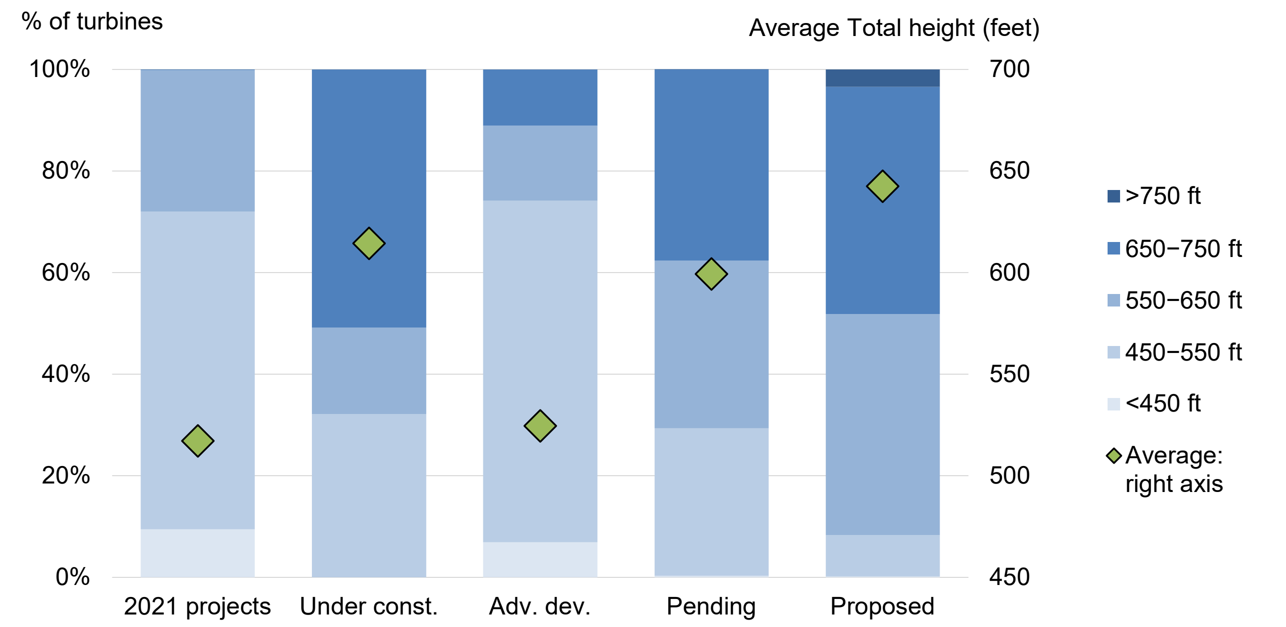


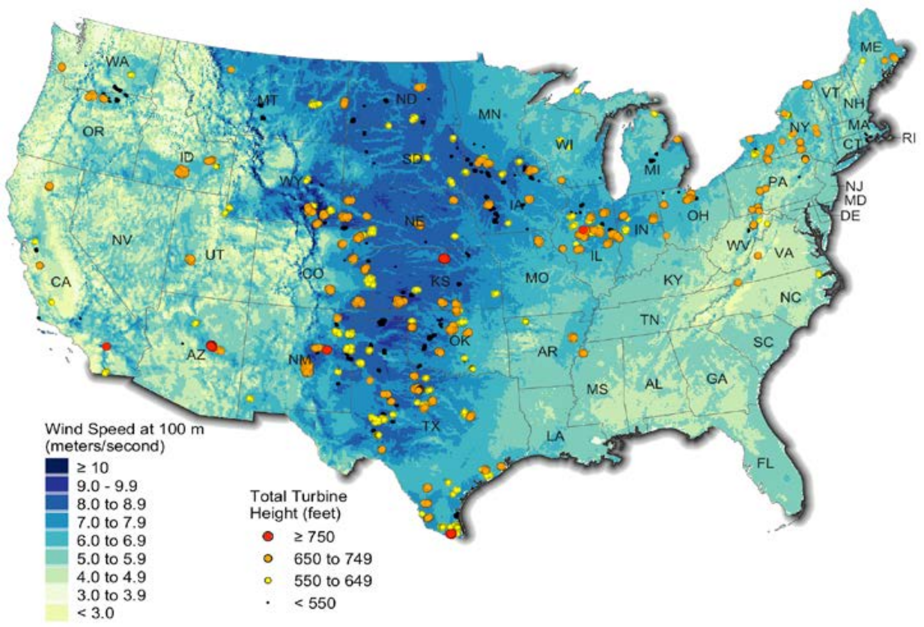
Sources: ACP, U.S. Wind Turbine Database, AWS Truepower, Berkeley Lab

Interactive data visualization: https://emp.lbl.gov/wind-power-technology-trends

Wind projects planned for the near future are poised to continue the trend of ever-taller turbines

Proposed turbines show significant growth in total turbine height, compared to 2021 projects





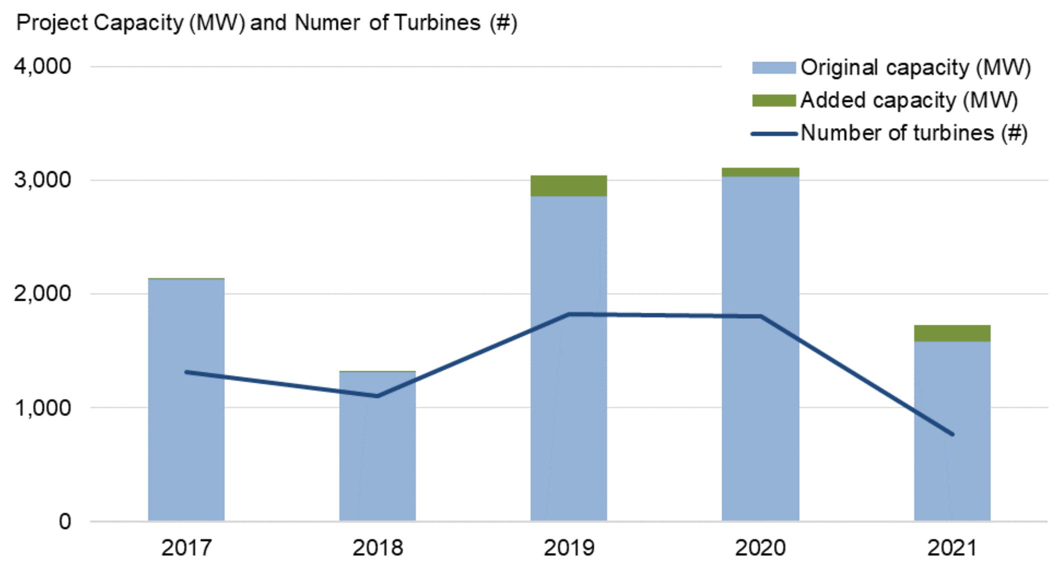
FAA = Federal Aviation Administration

Sources: ACP, FAA files, AWS Truepower, Berkeley Lab

In 2021, 12 wind projects were partially repowered, most of which now feature significantly larger rotors and lower specific power ratings

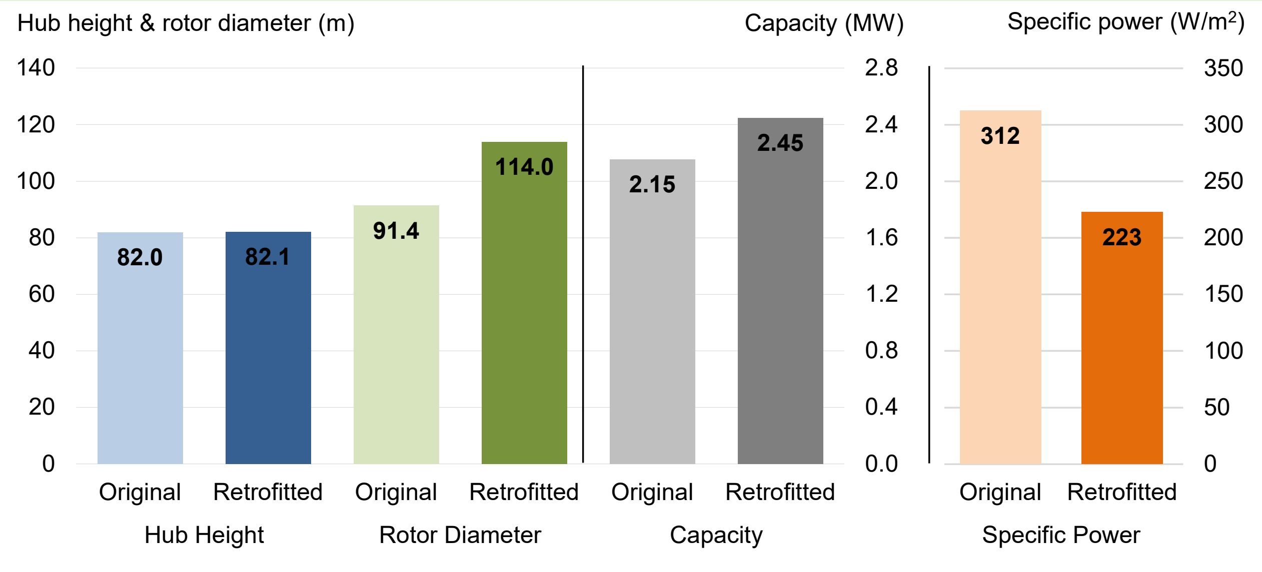
Partial Repowering by Year

(Figure shows wind project capacity repowered each year)



Technology Change with Partial Repowering

(Figure shows average technology change for wind turbines repowered in 2021)

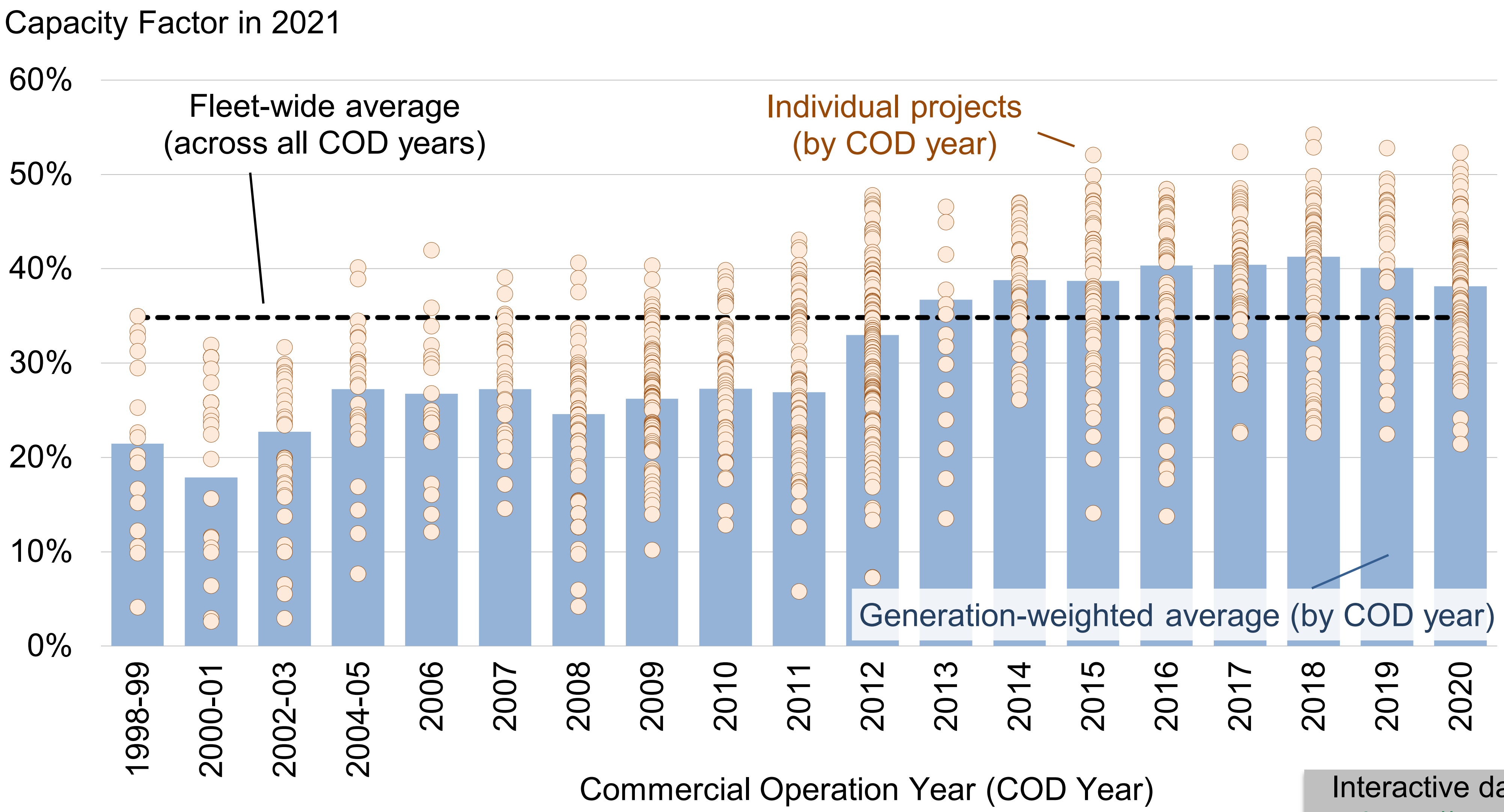


Sources: ACP, Berkeley Lab, turbine manufacturers

The mean age of turbines retrofitted in 2021 was just 10 years

Performance Trends

Average capacity factor 35% on a fleet-wide basis and 39% among projects built more recently; trending lower in most recent years

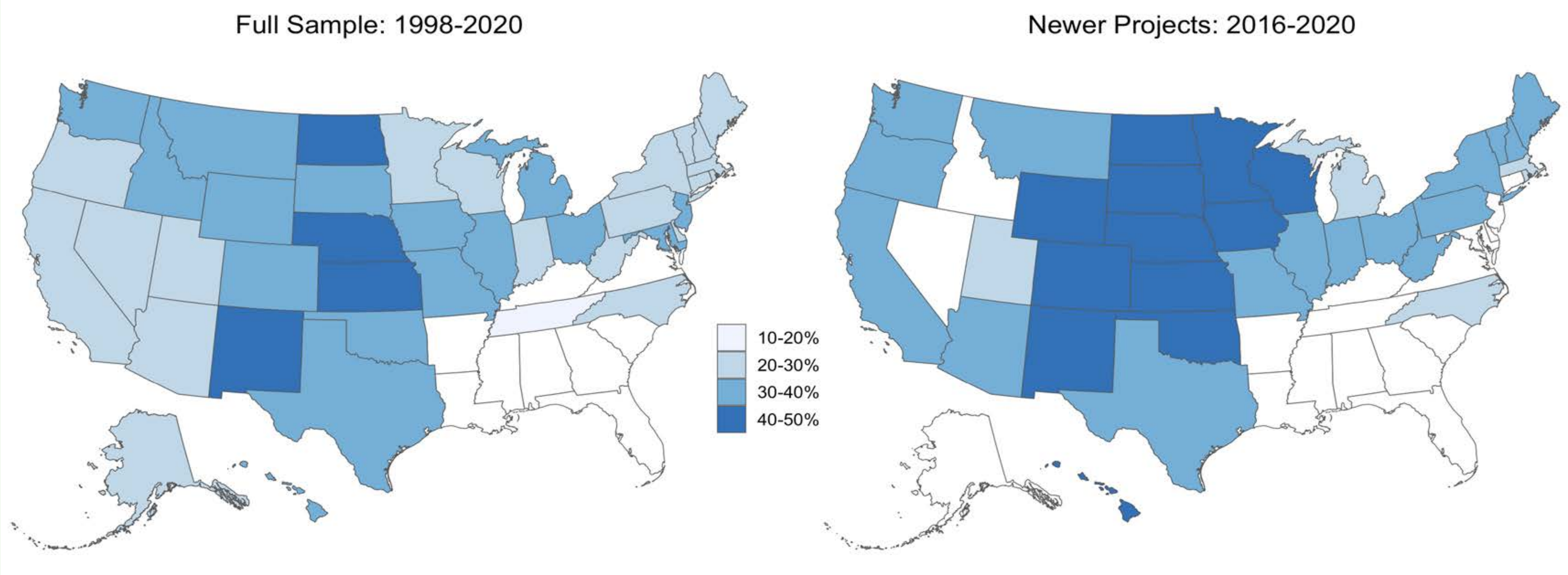


Interactive data visualization: https://emp.lbl.gov/wind-power-performance

Source: EIA, FERC, Berkeley Lab

The central part of the country features the highest capacity factors, in part reflecting the strength of the wind resource

Newer projects (right figure) have considerably higher capacity factors than the full sample of 1998—2030 projects (left figure)

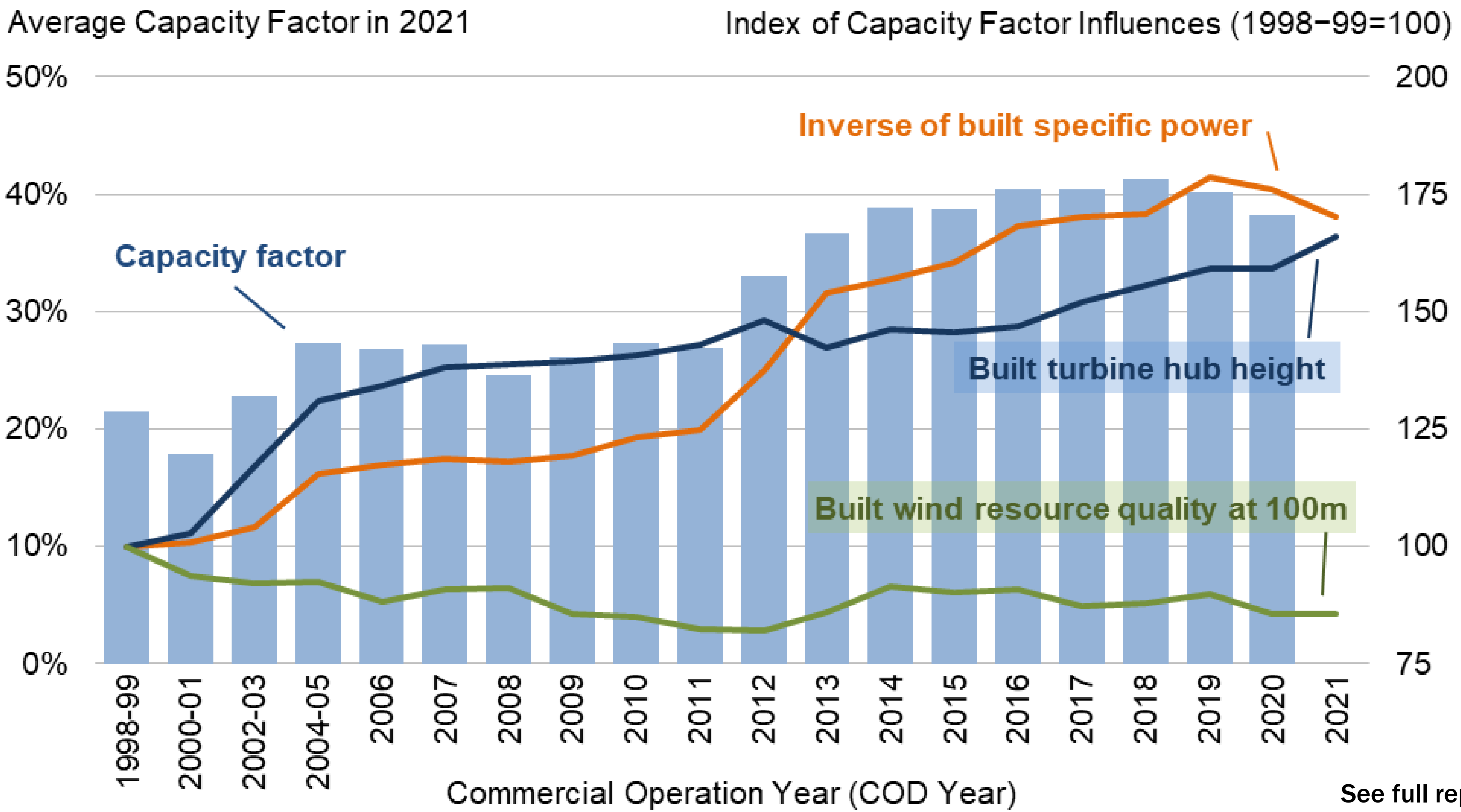


Source: EIA, FERC, Berkeley Lab

Note: States shaded in white have no projects in full sample (left) or in newer sample (right)

Interactive data visualization: https://emp.lbl.gov/wind-power-performance

Turbine design and site characteristics influence performance; 2021 projects impacted by recent specific power and resource quality trends

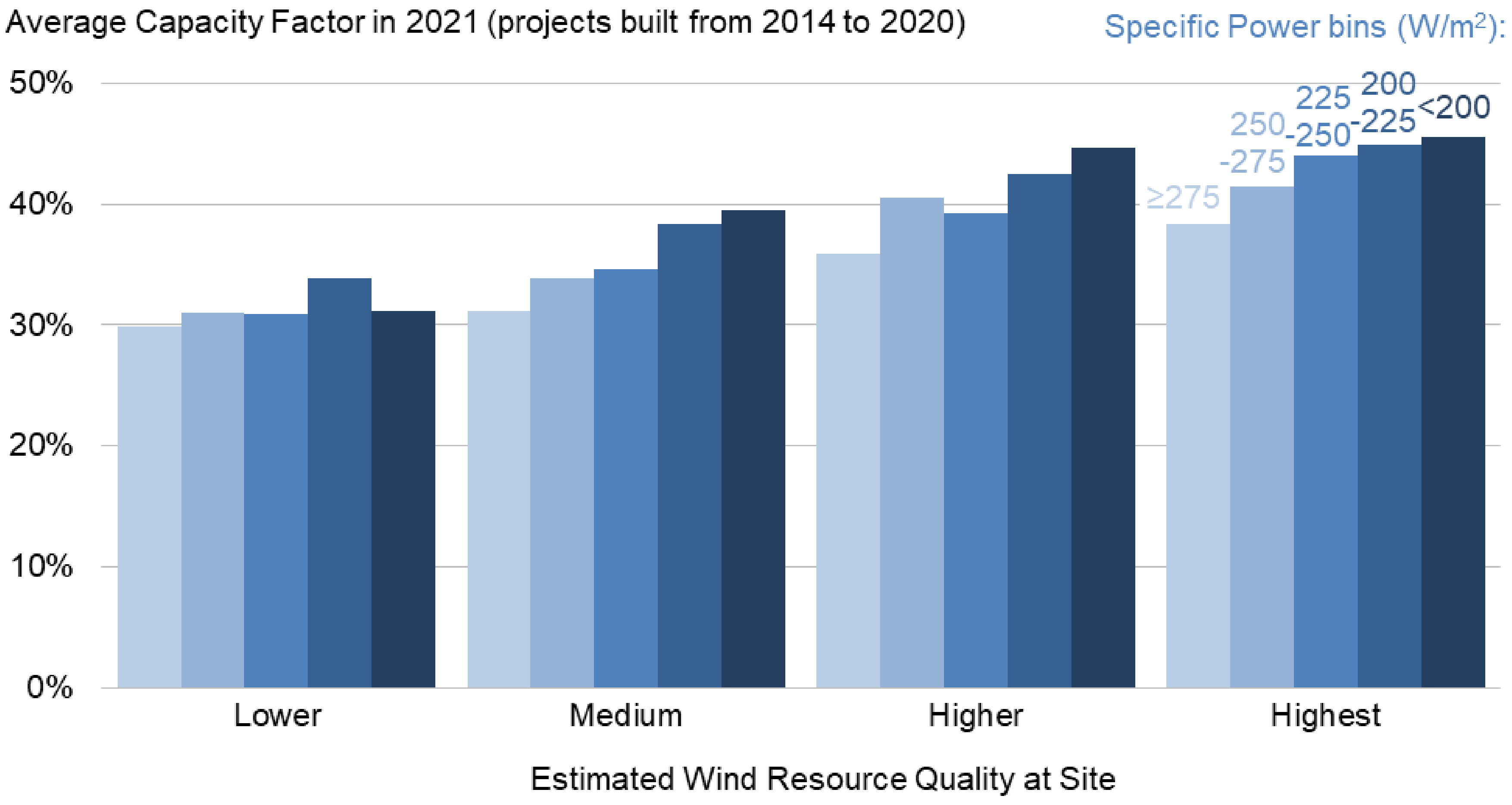


Source: EIA, FERC, Berkeley Lab

See full report for details on and interpretation of figure

Controlling for wind resource quality and specific power demonstrates impact of turbine evolution

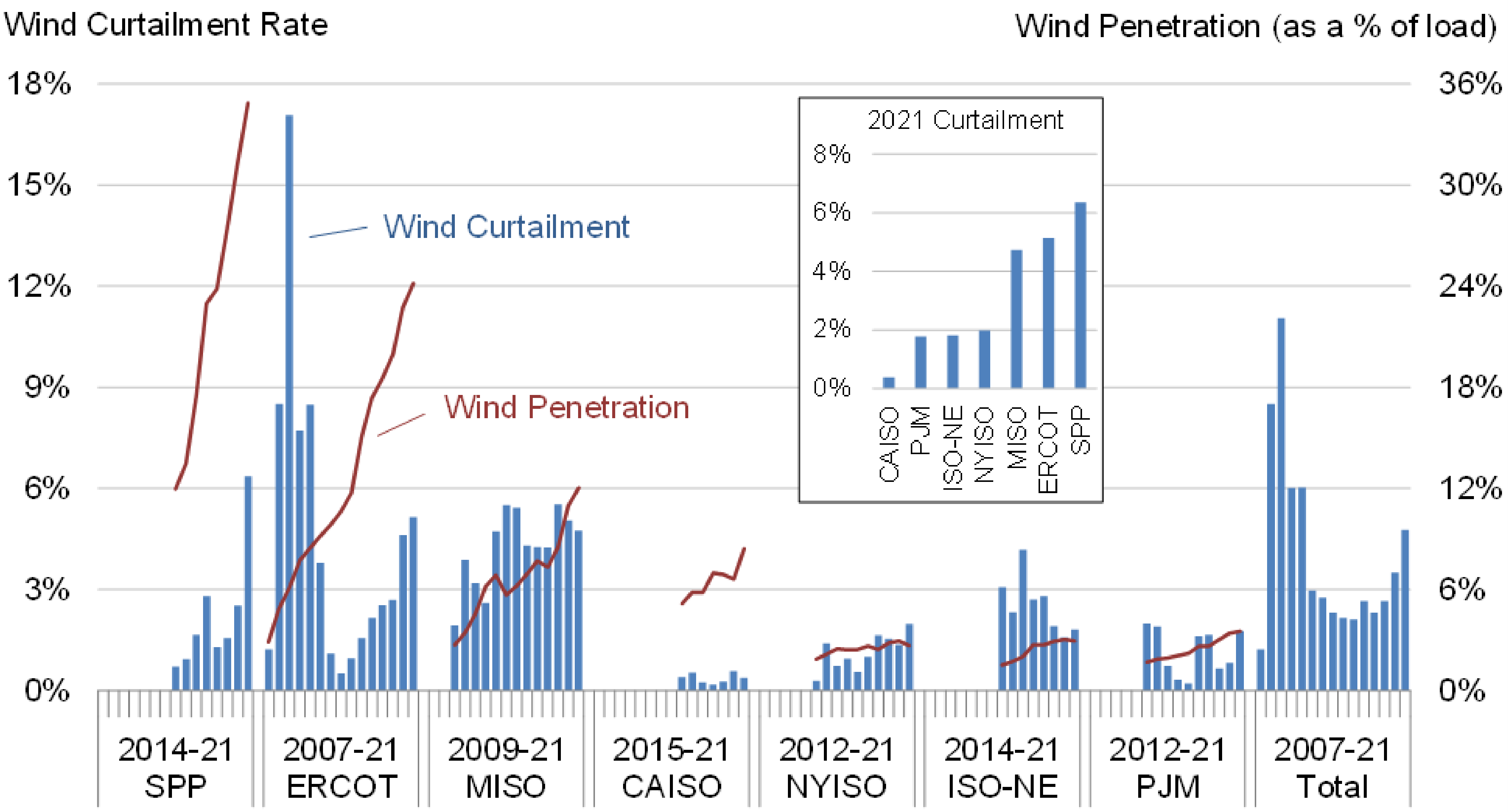
Low specific power turbines have driven capacity factors higher for projects located in given wind resource regimes



Note: See full report for a description of this categorization of wind resource quality

Source: EIA, FERC, Berkeley Lab

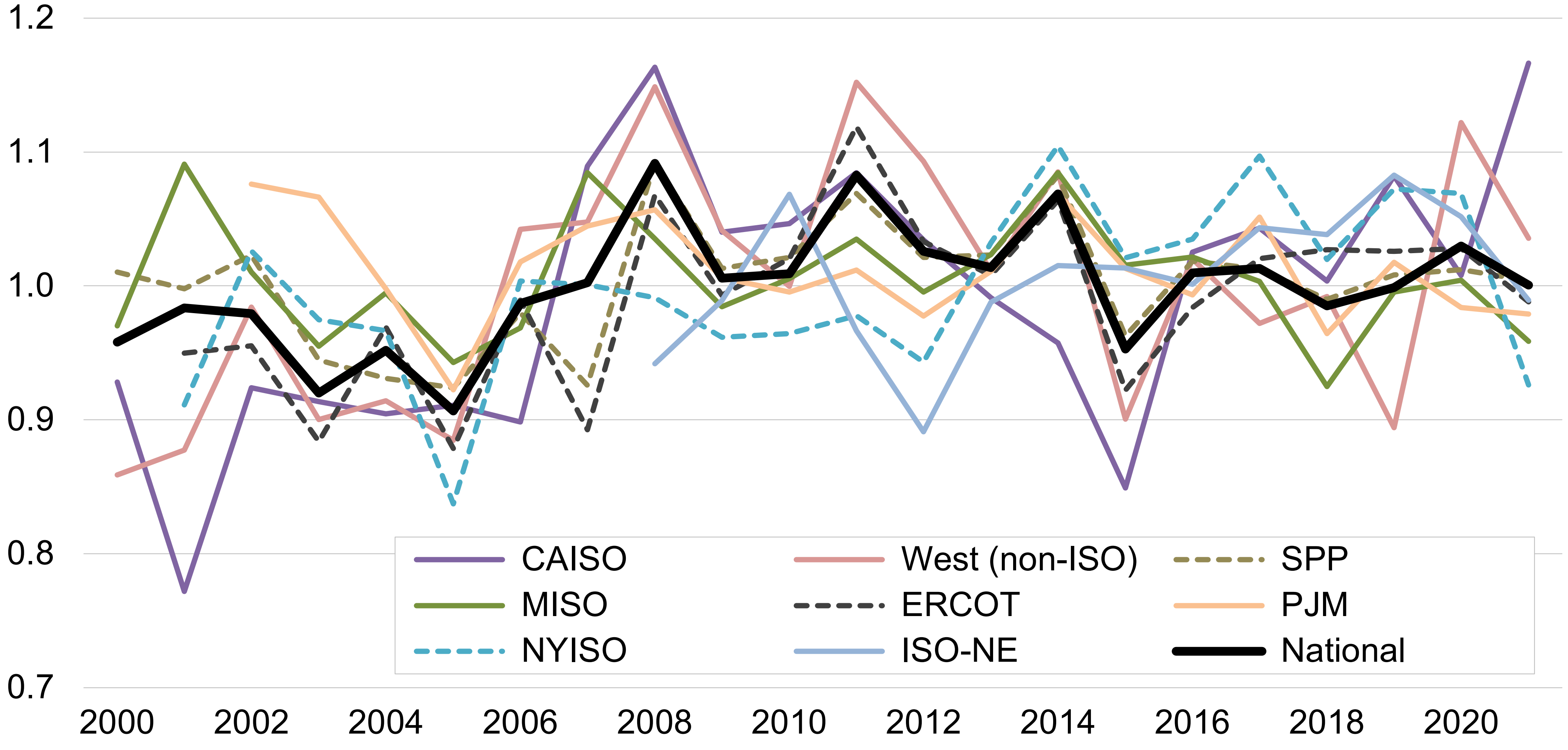
Wind power curtailment in 2021 across seven regions averaged 4.8%, up from a low of 2.1% in 2016



Sources: ERCOT, MISO, CAISO, NYISO, PJM, ISO-NE, SPP

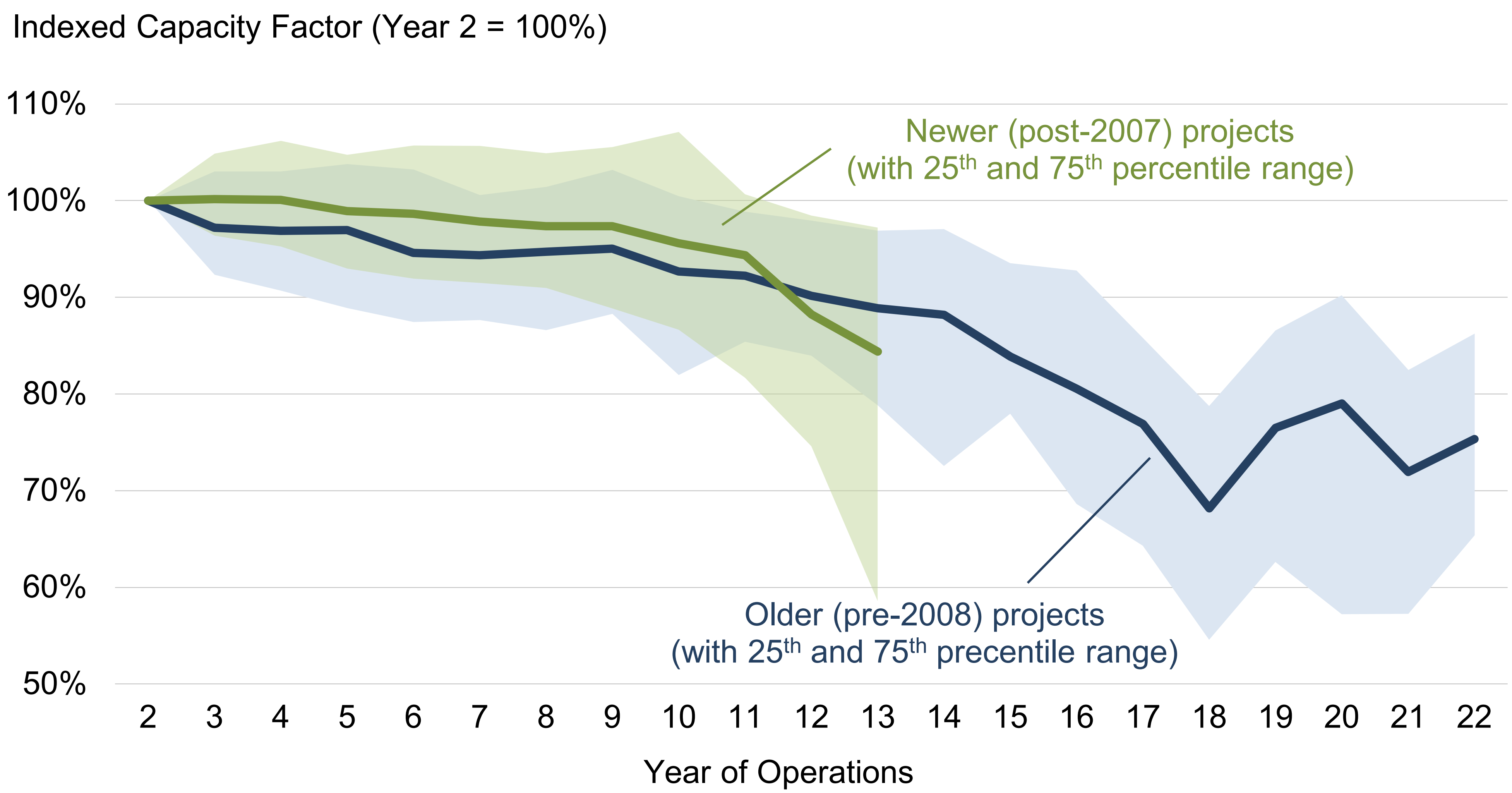
Yearly variations in average wind speed impact project performance; 2021 wind speeds were near the long-term average for most regions

Average Annual Wind Resource Indices (Long-Term Average = 1.0)



Source: ERA, Berkeley Lab; methodology behind the index of inter-annual variability is explained in report appendix

Wind project performance degradation with project age also explains why older projects did not perform as well in 2021



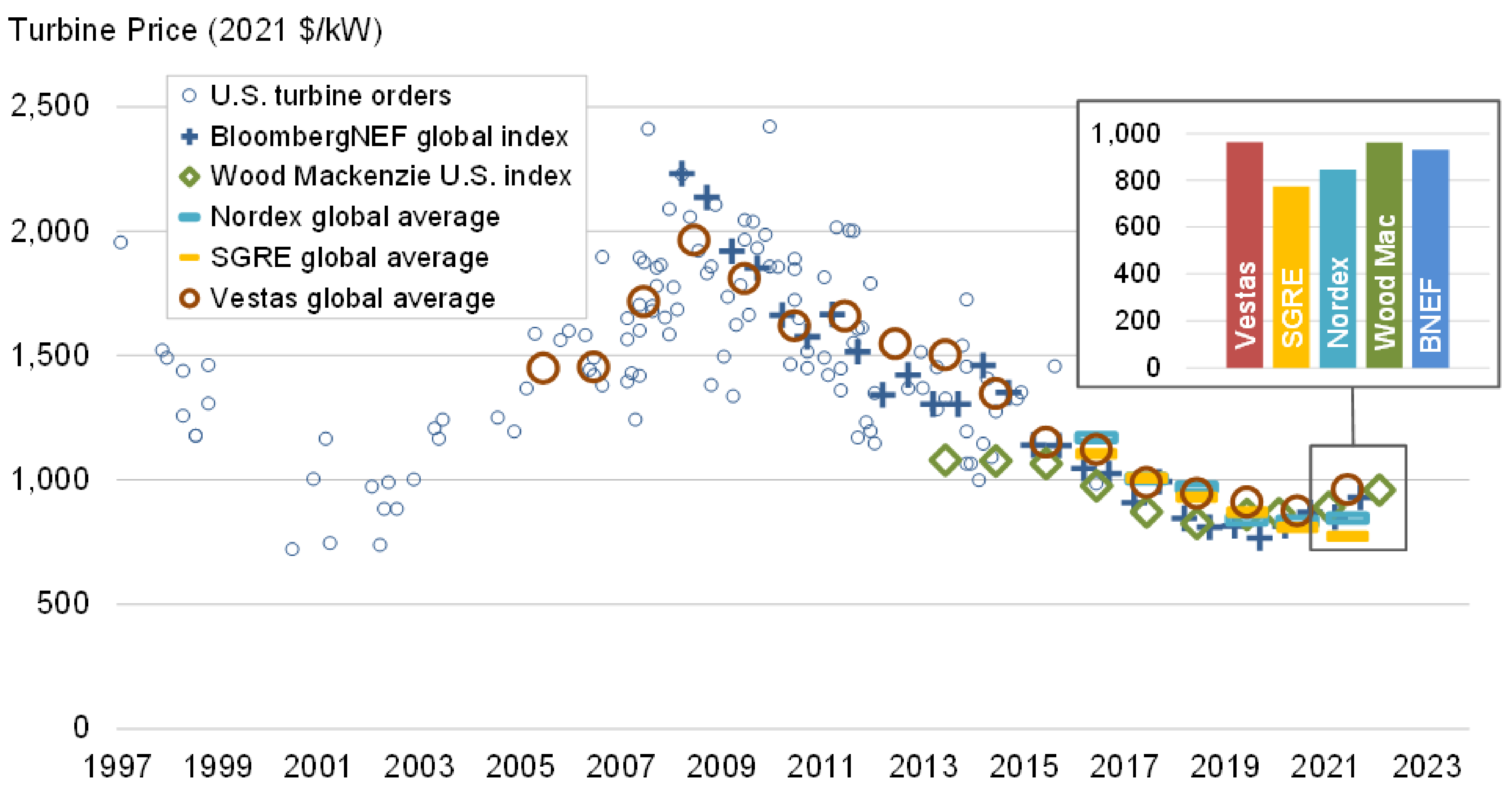
Performance decline after year 10 may, in part, reflect operational choices impacted by the federal PTC

Source: EIA, FERC, Berkeley Lab

For more analysis on wind project performance with plant age, see: https://emp.lbl.gov/publications/how-does-wind-project-performance

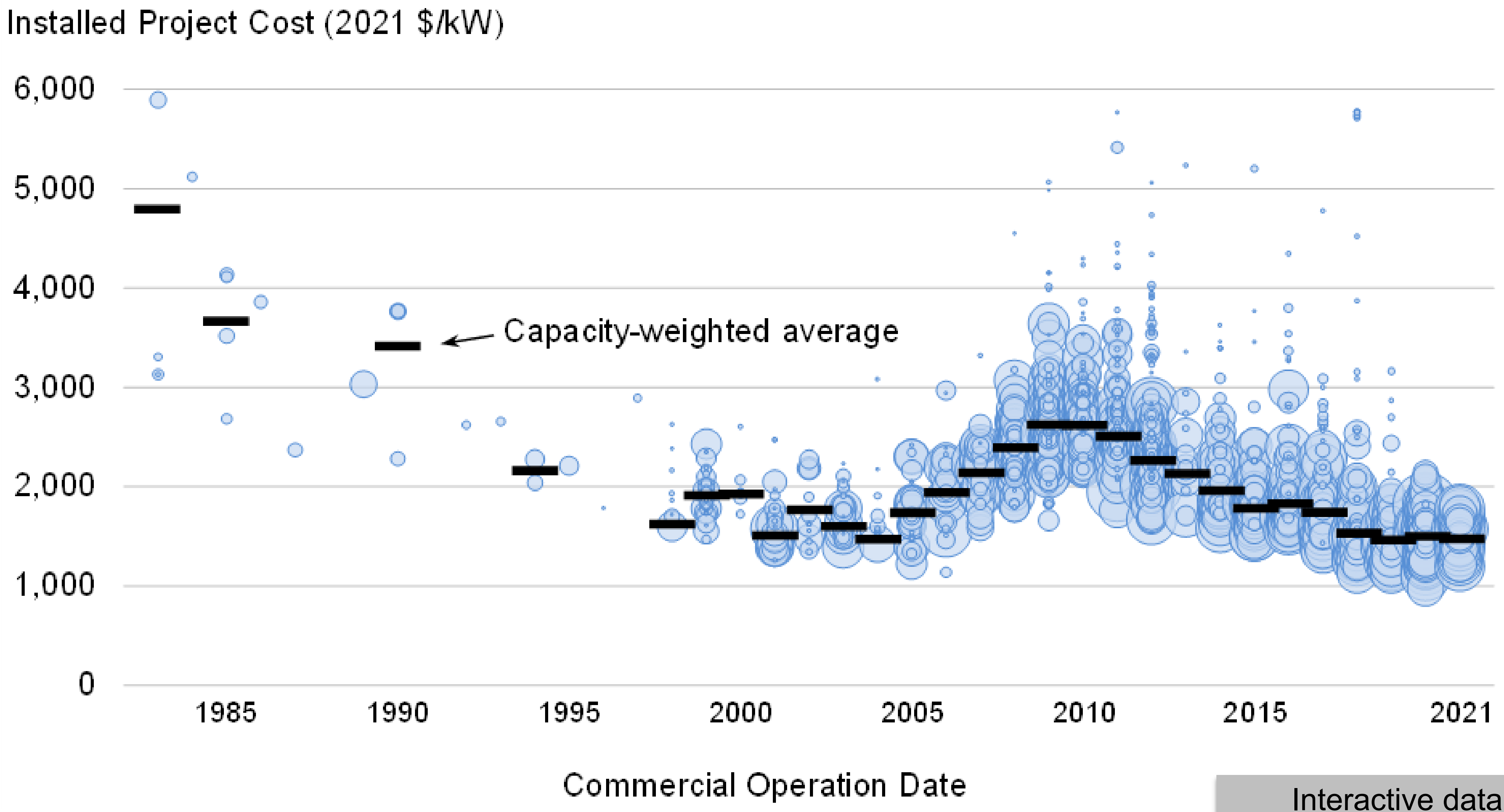
Cost Trends

Wind turbine prices increased by an average of 5% to 10% in 2021 given supply chain pressures: ~$800-950/kW in 2021



Sources: Berkeley Lab, annual financial reports, forecast providers

Installed project costs in 2021 held steady at an average of $1,500/kW even as turbine prices rose

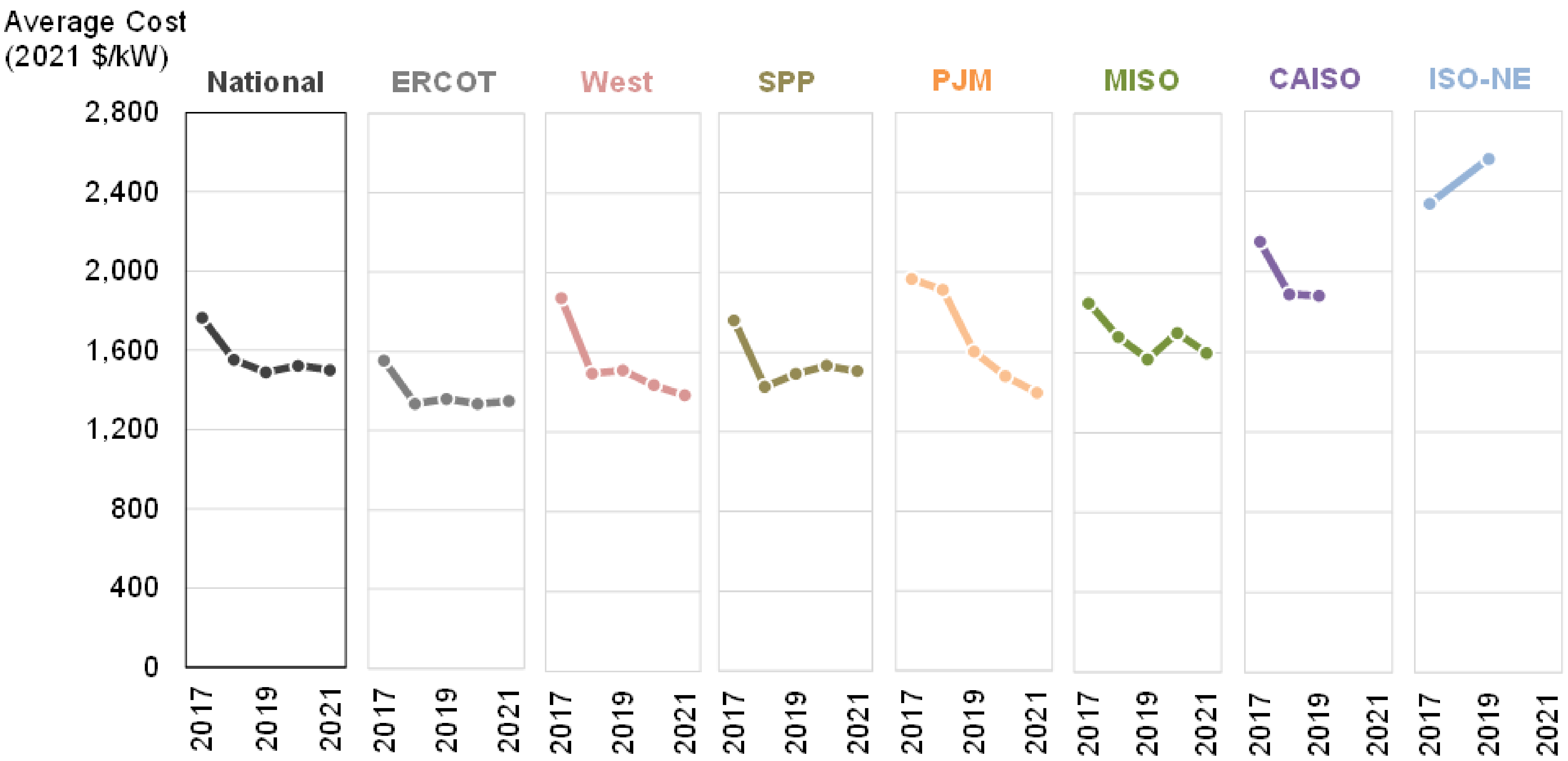


Note: Size of "bubble" reflects project capacity

Sources: Berkeley Lab, EIA (some data points suppressed to protect confidentiality)

Interactive data visualization: https://emp.lbl.gov/wind-energy-capital-expenditures-capex

General five-year trend towards lower installed project costs exists across most regions of the United States

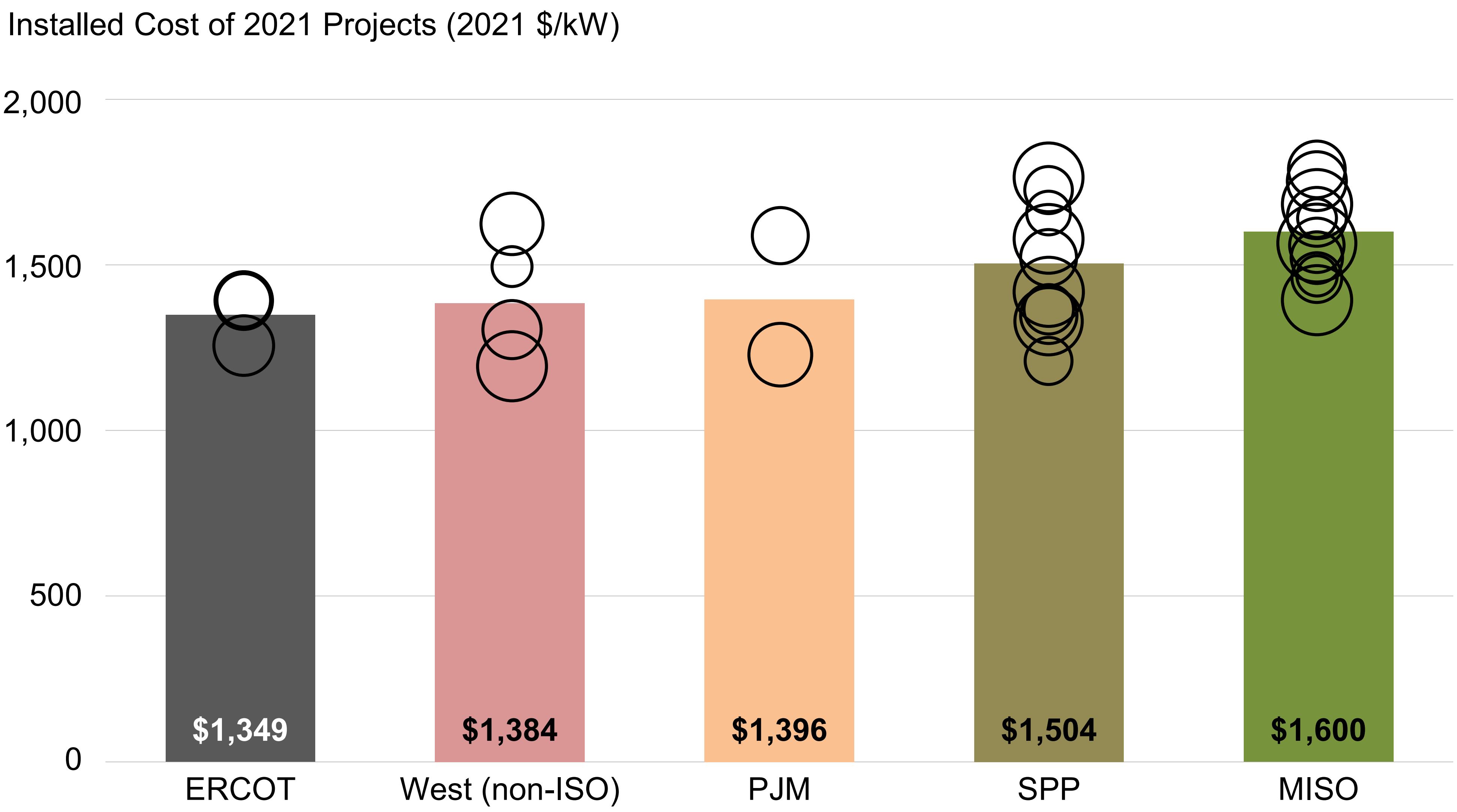


Sources: Berkeley Lab, EIA

Note: NYISO data are not available over this period. For other regions, data for specific years are missing.

Interactive data visualization: https://emp.lbl.gov/wind-energy-capital-expenditures-capex

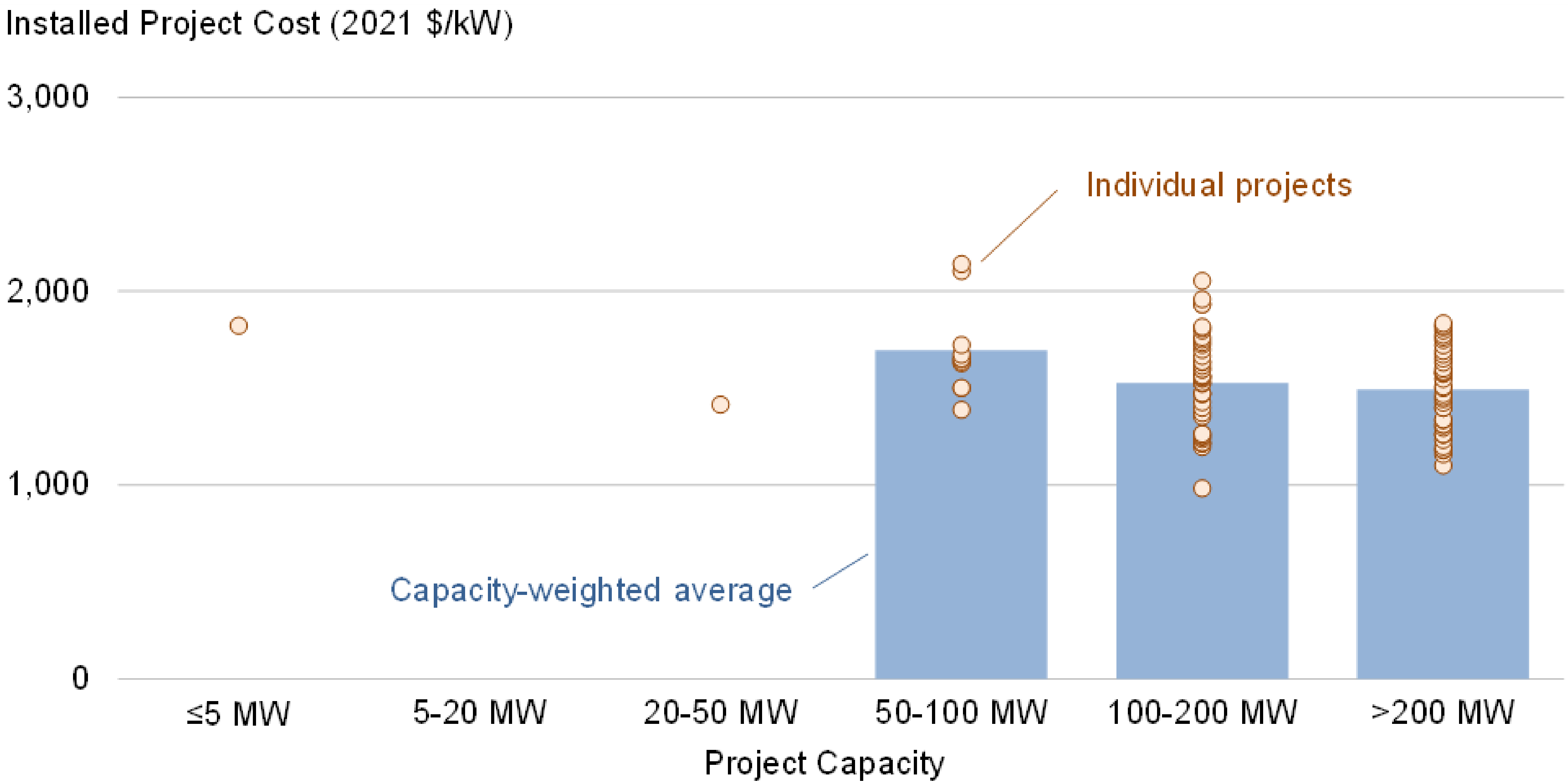
Regional differences in average wind project costs in 2021 are apparent, but sample size is limited in some regions



Note: Size of "bubble" reflects project capacity
Source: Berkeley Lab

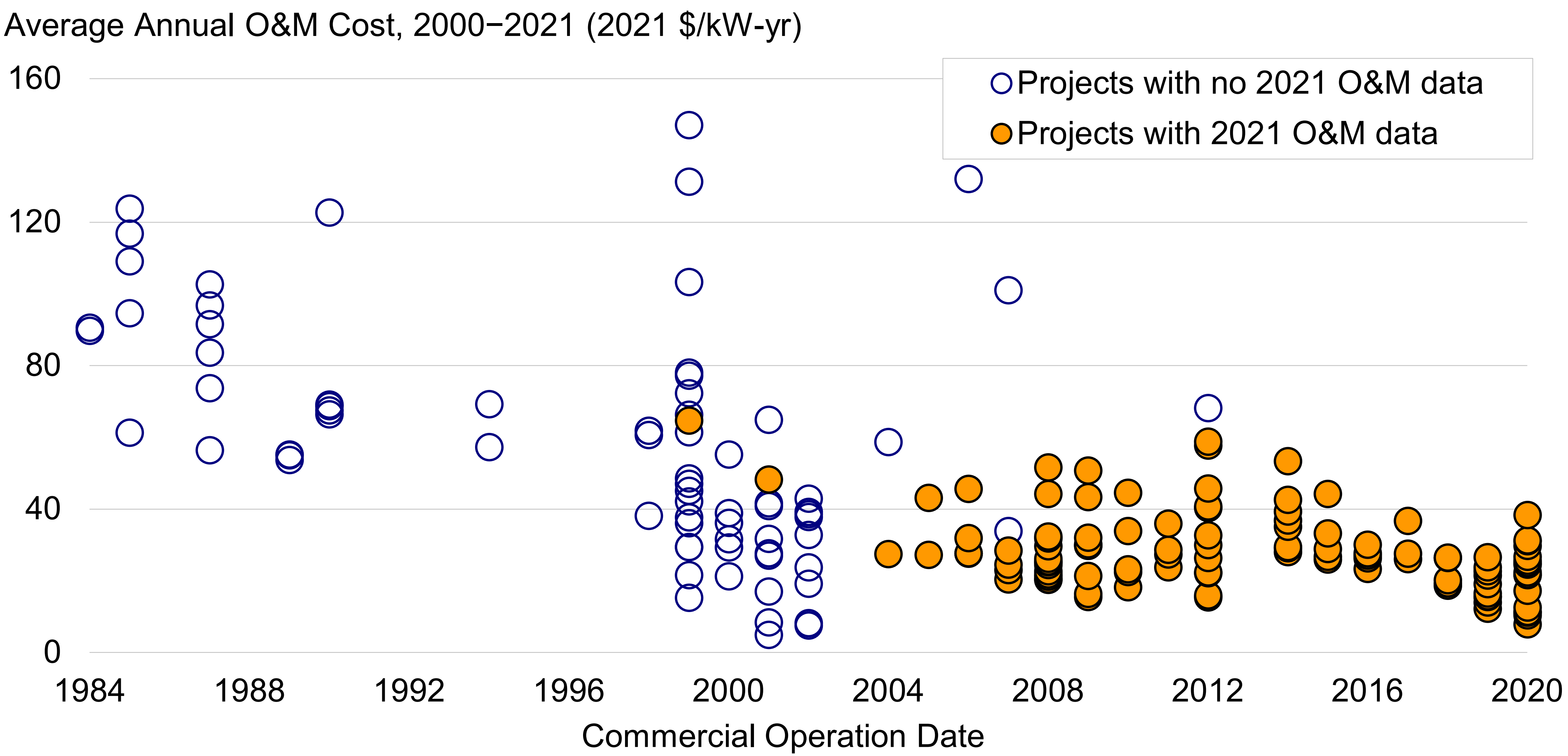
Interactive data visualization: https://emp.lbl.gov/wind-energy-capital-expenditures-capex

Installed costs generally decline with project size; are lowest for projects over 200 MW among 2020 and 2021 projects



Source: Berkeley Lab

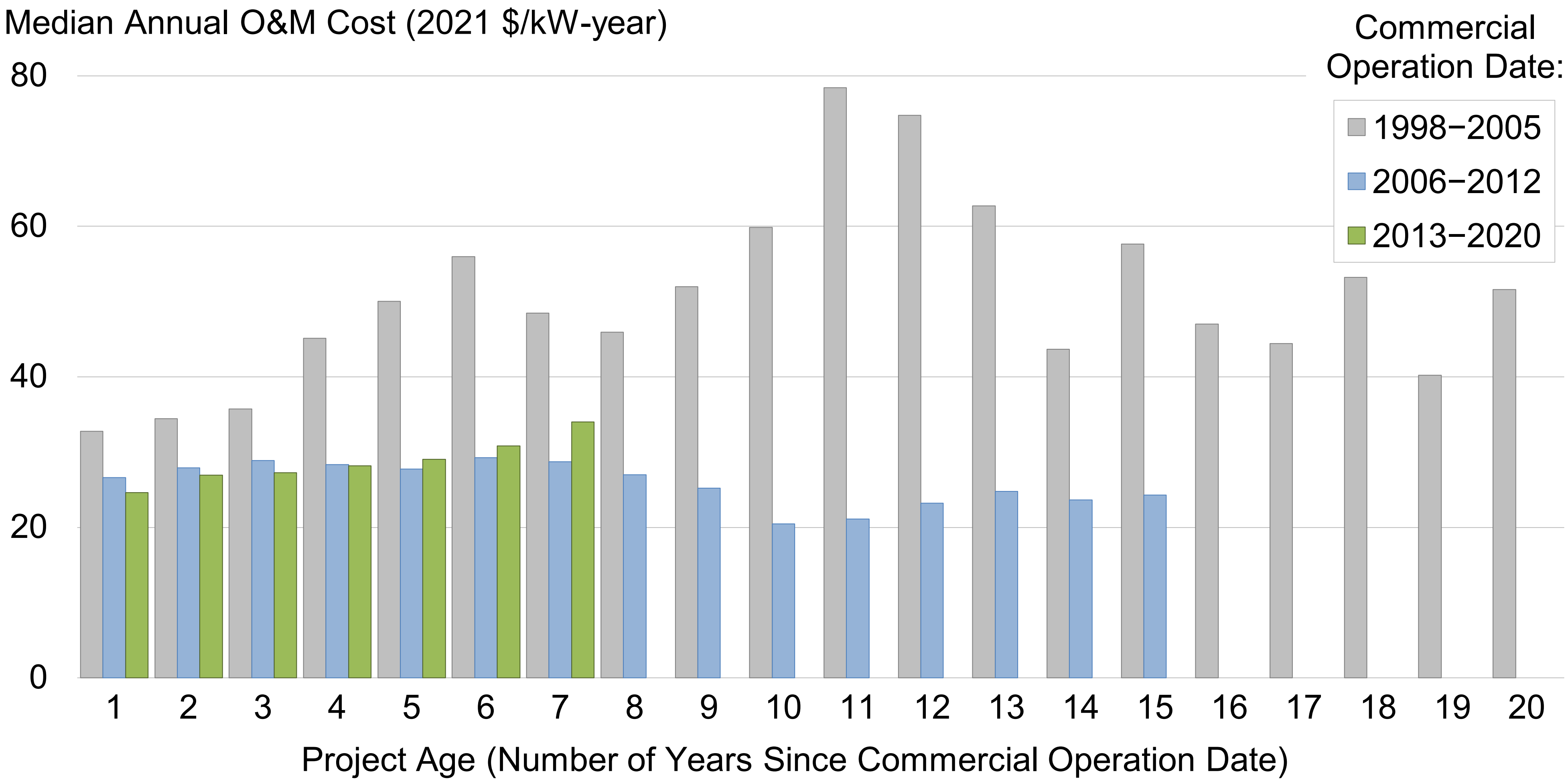
Operations and maintenance (O&M) costs vary by commercial operations date and project age



Source: Berkeley Lab; some data points suppressed to protect confidentiality

Note: Sample is limited; few projects in sample have complete records of O&M costs from 2000-20; O&M costs reported here do not include all operating costs.

O&M costs are lower for more-recently built projects, but cost trends as projects age do not follow consistent patterns



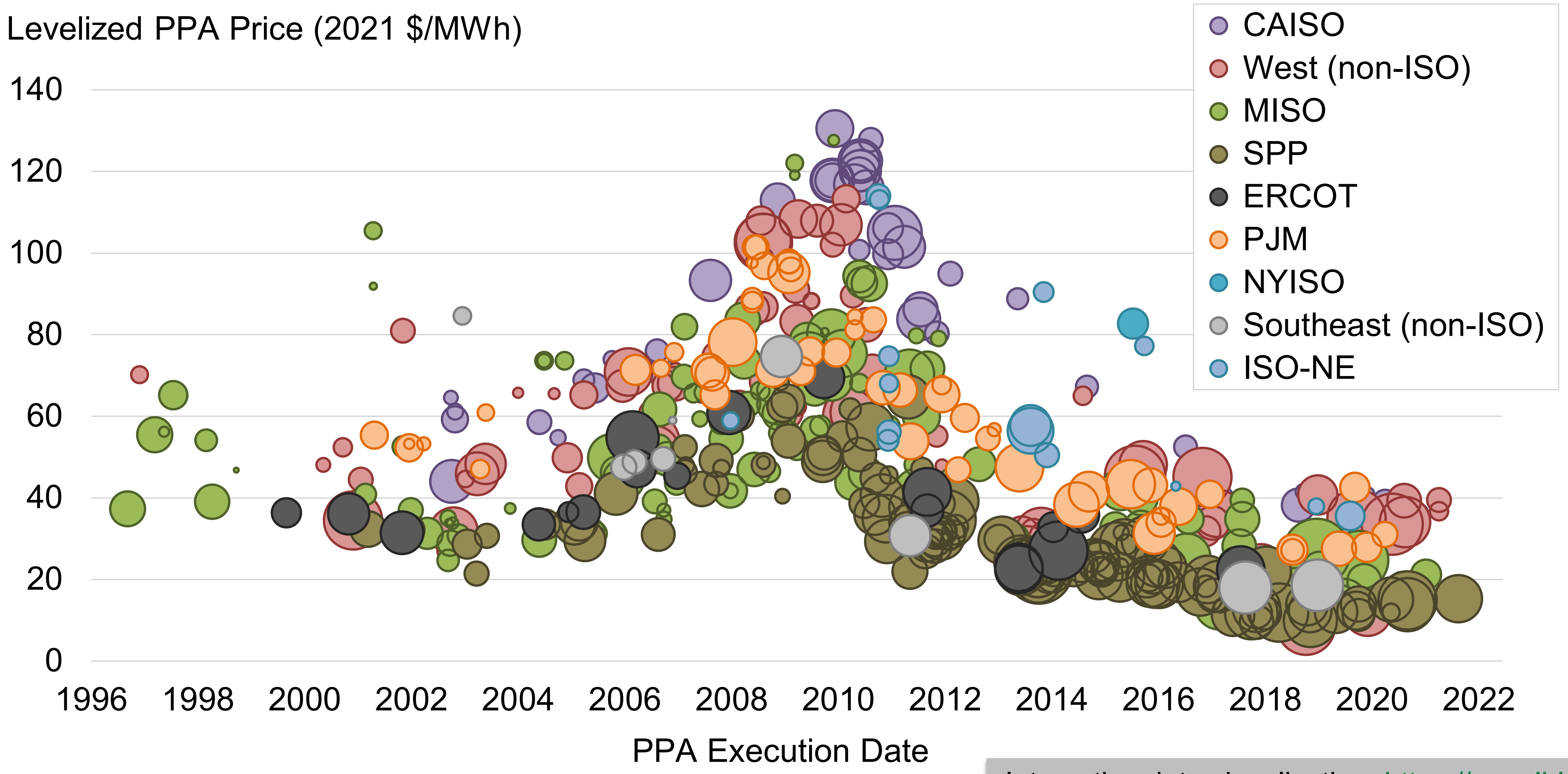
O&M reported here does not include all operating costs: all-in operating costs for the most recent wind projects average >$40/kW-year

Source: Berkeley Lab; medians shown only for groups of two or more projects, and only projects >5 MW are included

Note: Sample size is limited, especially in years 15-20

Power Sales Price and Levelized Cost Trends

Wind power purchase agreement (PPA) prices have been drifting higher, following turbine price trends, but generally remain low

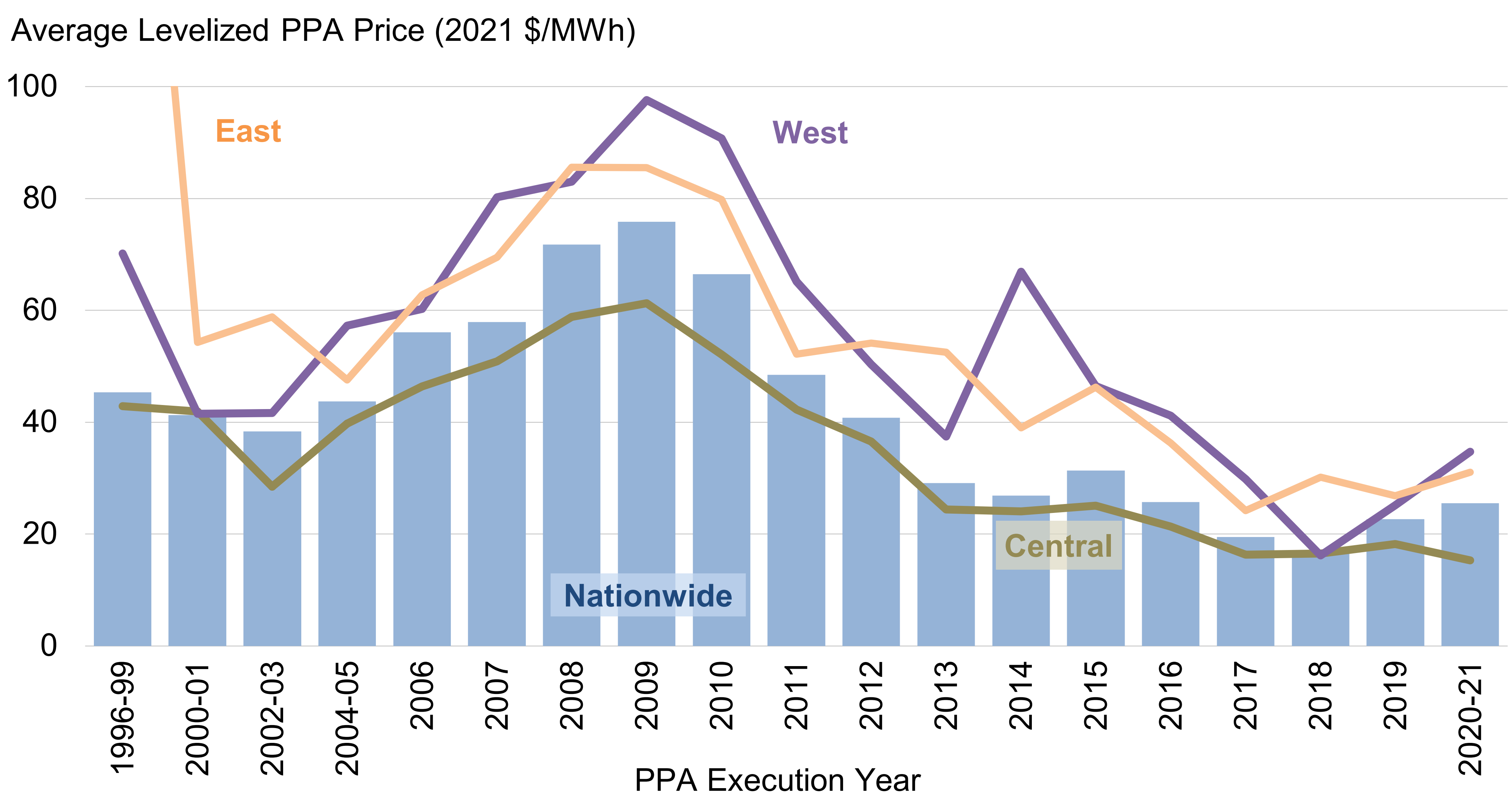


Interactive data visualization: https://emp.lbl.gov/wind-power-purchase-agreement-ppa-prices

Note: Size of bubble reflects contract capacity

Source: Berkeley Lab, FERC

Average PPA prices have steeply declined since 2009; prices below $20/MWh in central region, but have been flat or risen in recent years

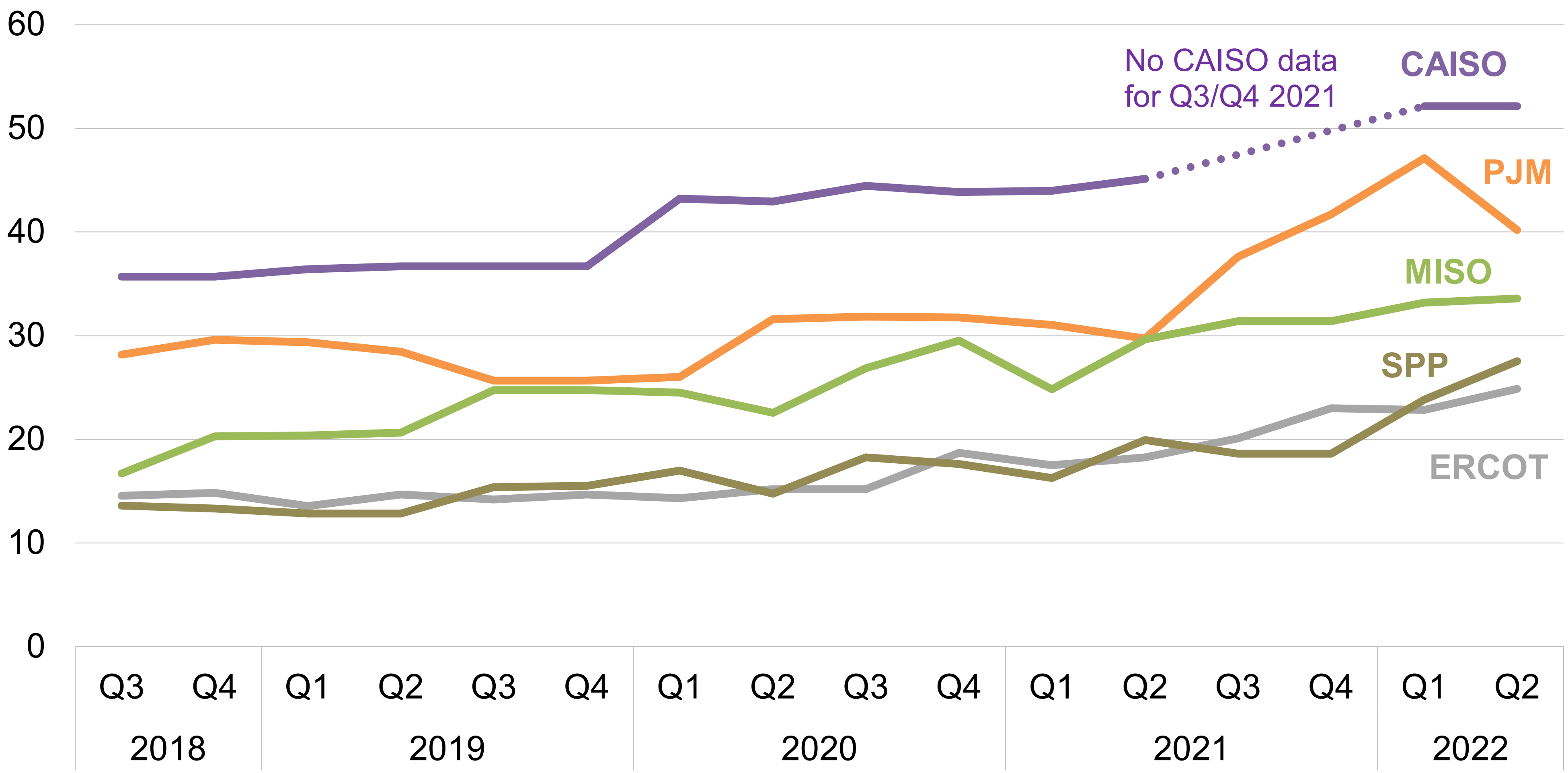


Source: Berkeley Lab, FERC

Note: West = CAISO, West (non-ISO); Central = MISO, SPP, ERCOT; East = PJM, NYISO, ISO-NE, Southeast (non-ISO)

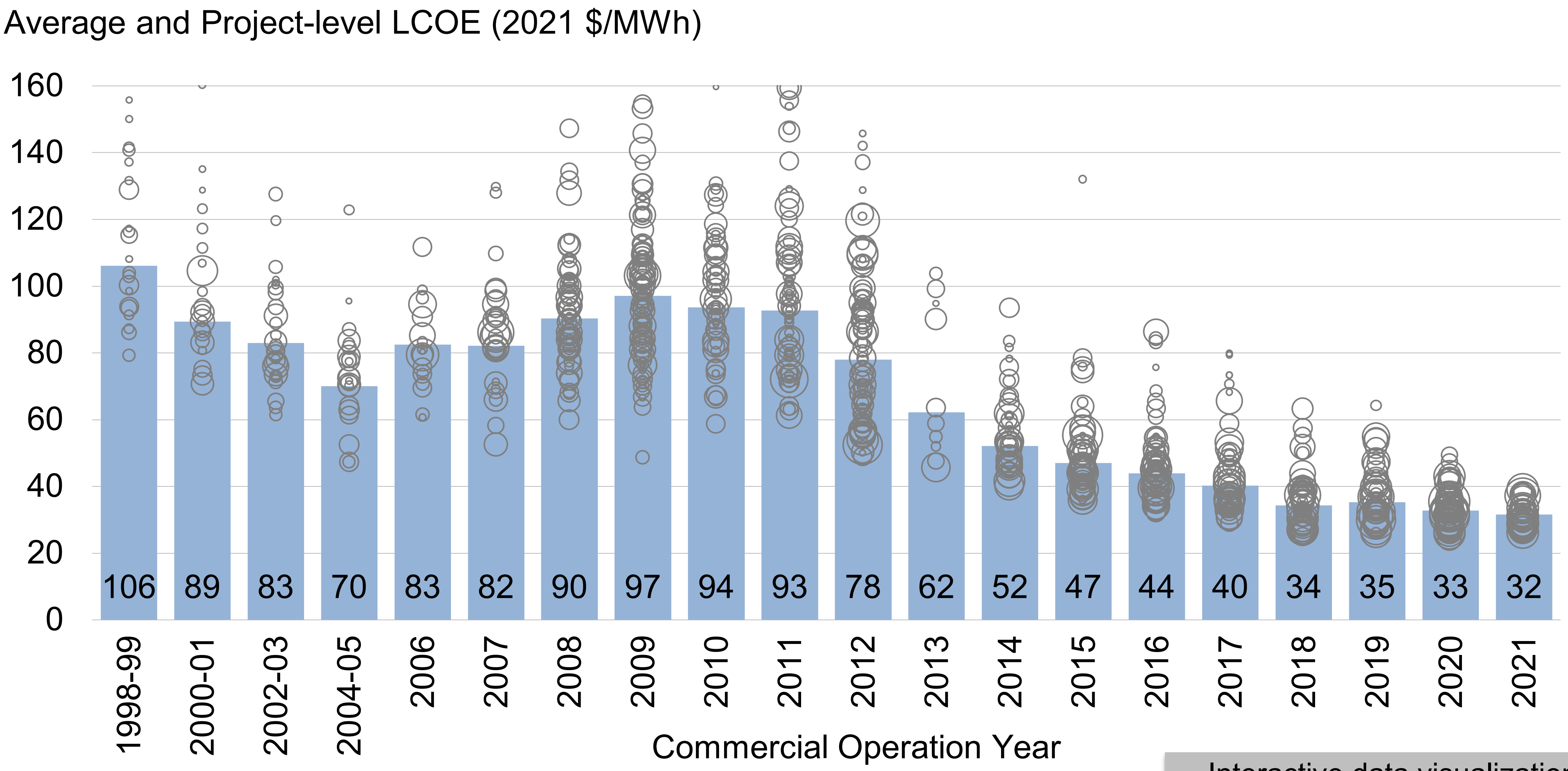
LevelTen Energy price indices confirm rising PPA prices, and regional variations in wind energy prices

Level10 PPA Price Index (2021 $/MWh, 25th percentile of offers)



Source: LevelTen Energy
Note: See full report for approach to converting nominal dollar LevelTen data to levelized real 2021$ as reported in figure above.

Levelized cost of wind energy (LCOE) has generally declined: nationwide average of $32/MWh for projects installed in 2021

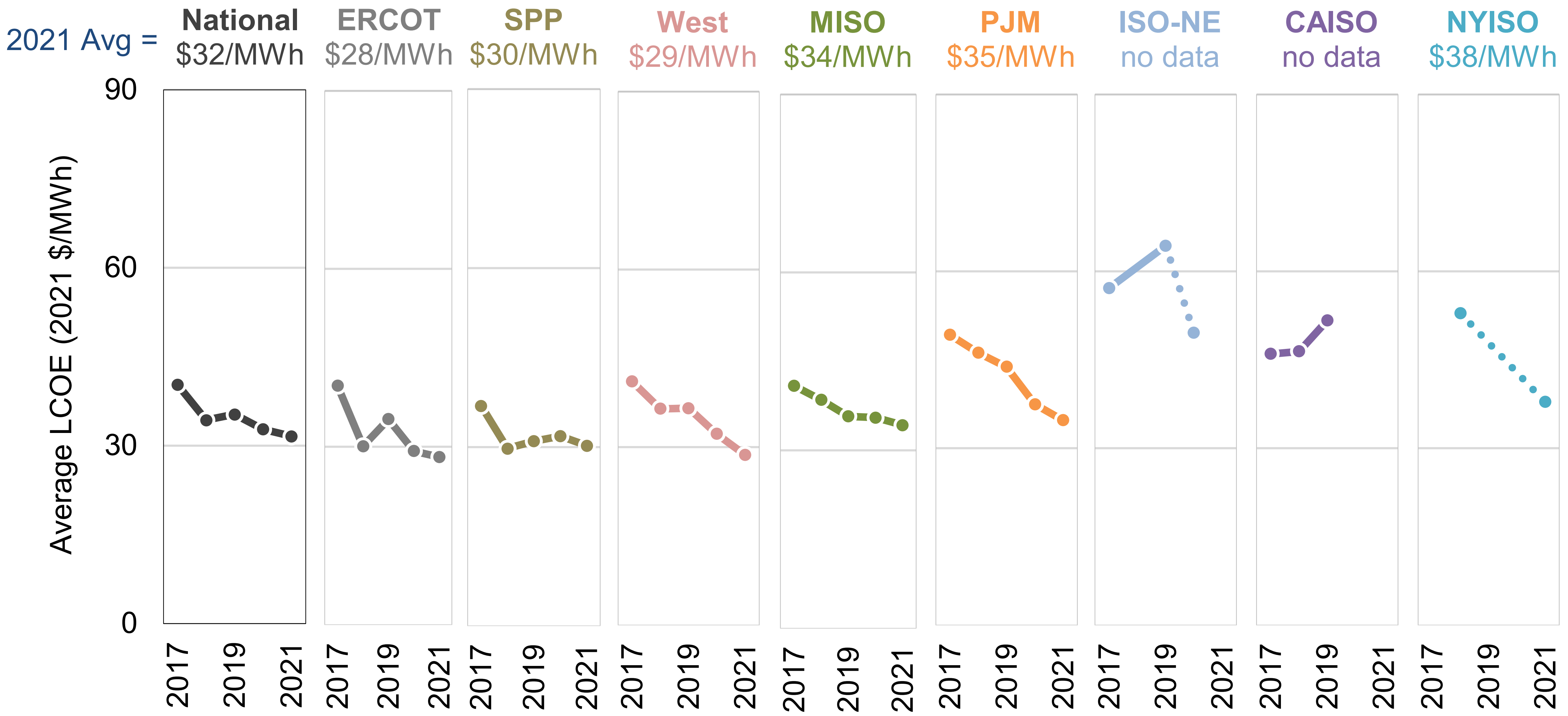


Source: Berkeley Lab

Note: Yearly estimates reflect variations in installed cost, capacity factors, operational costs, cost of financing, and project life; includes accelerated depreciation but exclude PTC. See full report for details.

Interactive data visualization: https://emp.lbl.gov/levelized-cost-wind-energy

Levelized costs vary by region, with the lowest costs in ERCOT, SPP, and the non-ISO West

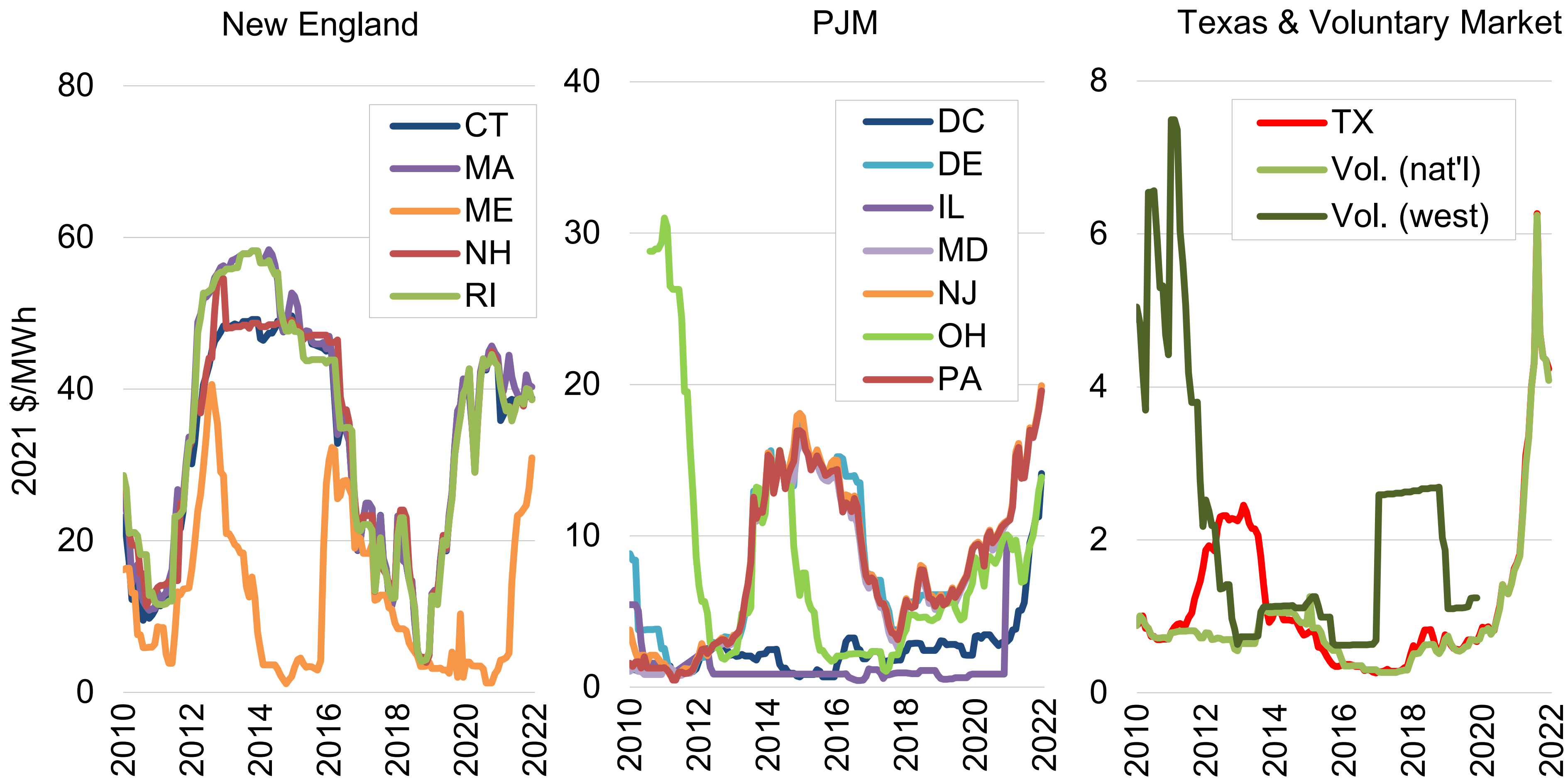


Source: Berkeley Lab

Note: Regional sample is limited in some regions and years

Interactive data visualization: https://emp.lbl.gov/levelized-cost-wind-energy

Renewable Energy Certificate (REC) prices continue to vary substantially across markets and time

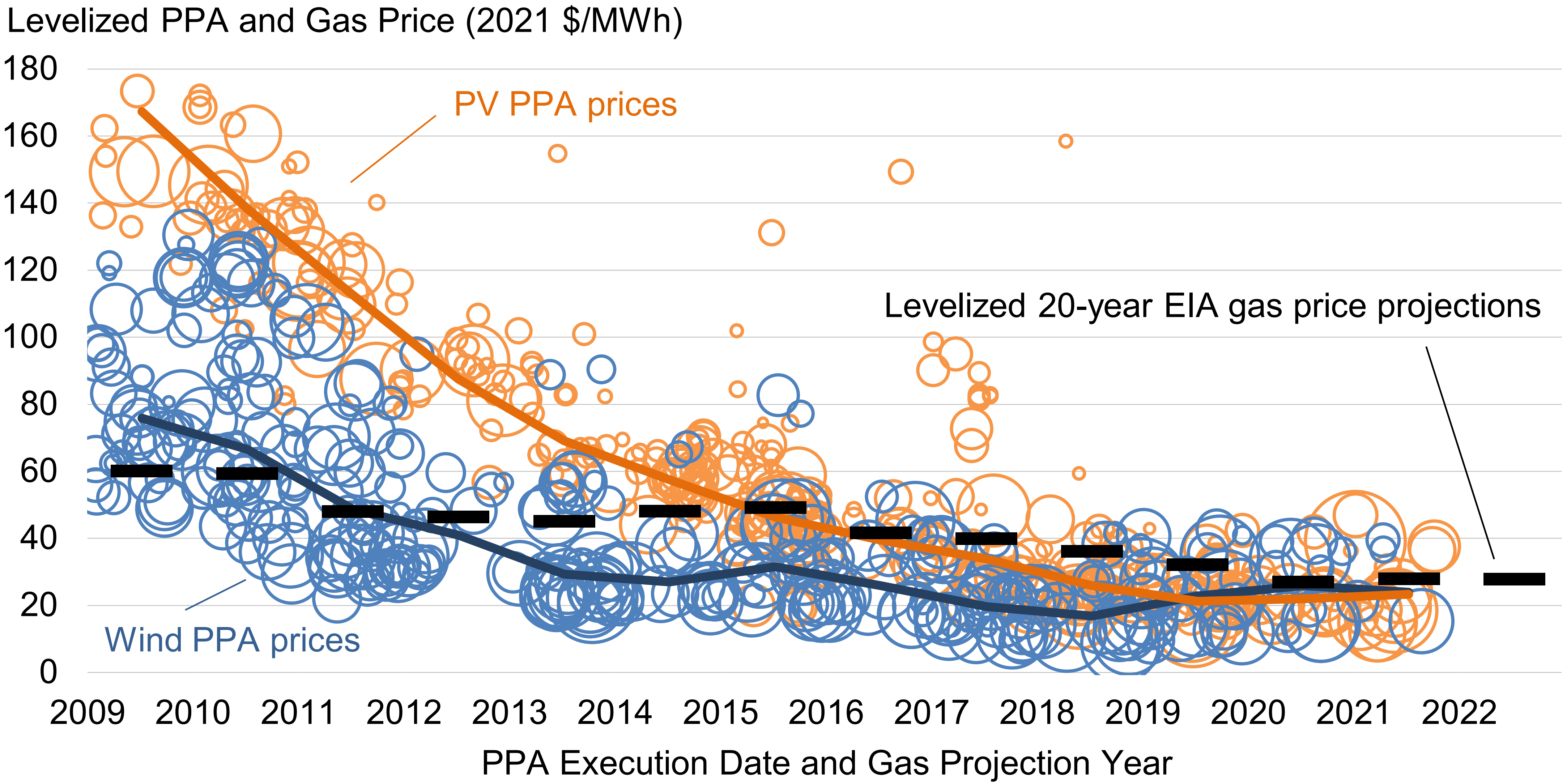


Source: Marex Spectron

REC prices vary by: market type (compliance vs. voluntary); geographic region; specific design of state RPS policies.

Cost and Value Comparisons

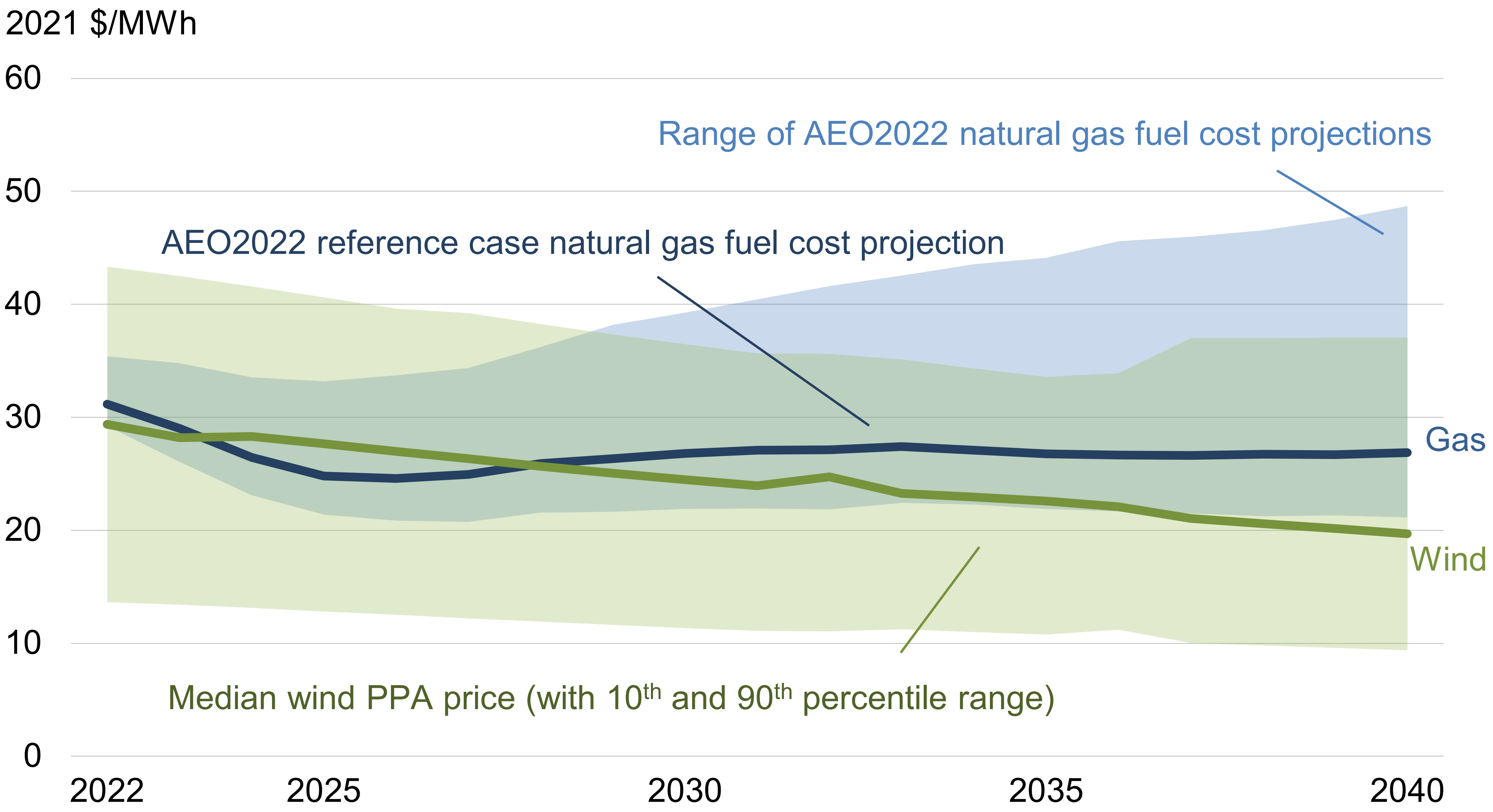
Despite low wind PPA prices, wind faces competition from solar and natural gas



Source: Berkeley Lab, FERC, EIA

Note: Smallest bubble sizes reflect smallest-volume PPAs (<5 MW), whereas largest reflect largest-volume PPAs (>500 MW).

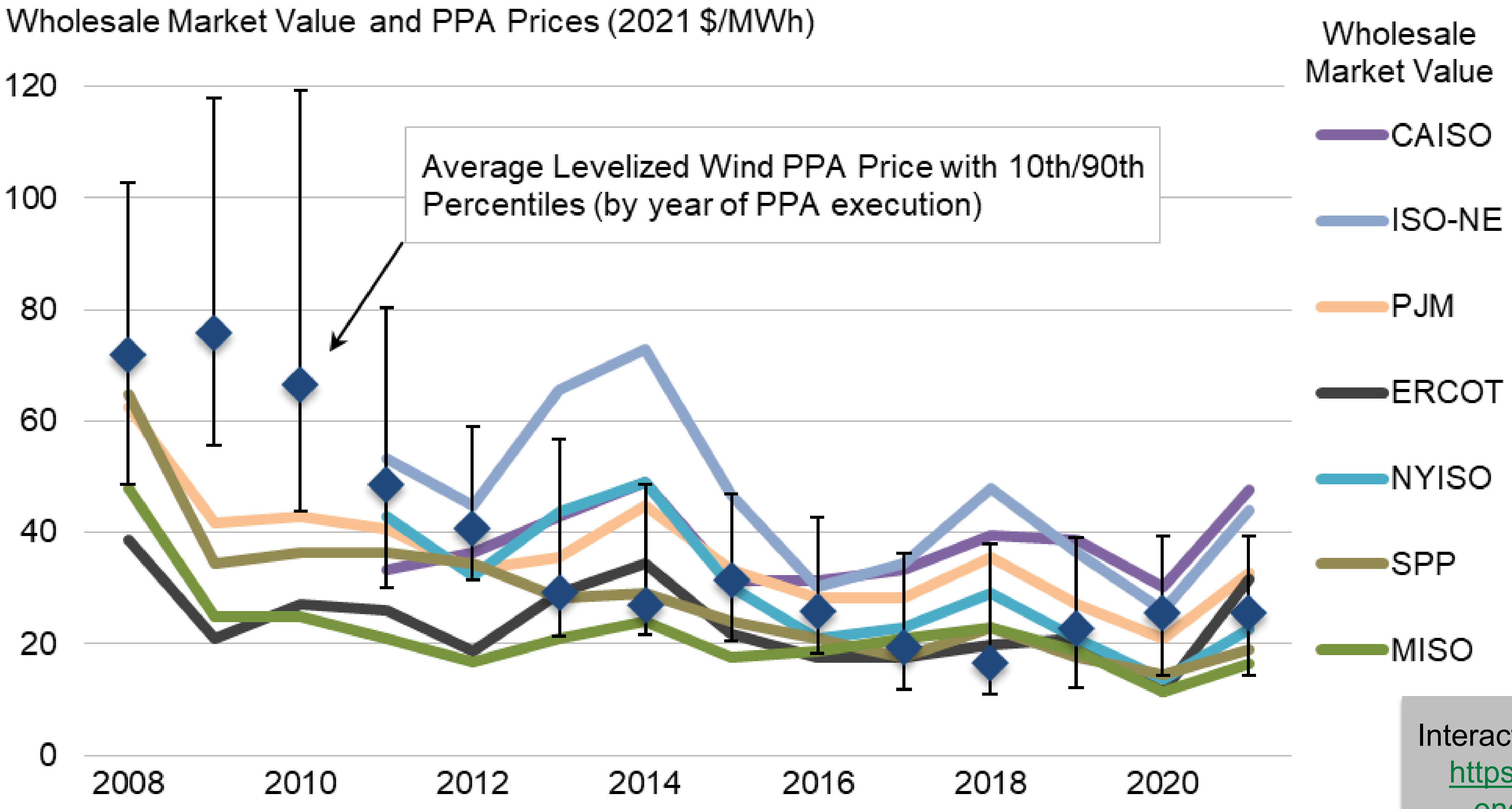
Recent wind prices are competitive with the expected future cost of burning fuel in natural gas plants



Source: Berkeley Lab, FERC, EIA

Notes: Price comparisons shown are far from perfect—see full report for details

The grid-system value of wind rebounded in 2021; roughly consistent with recent PPA prices of under $20/MWh to $40/MWh

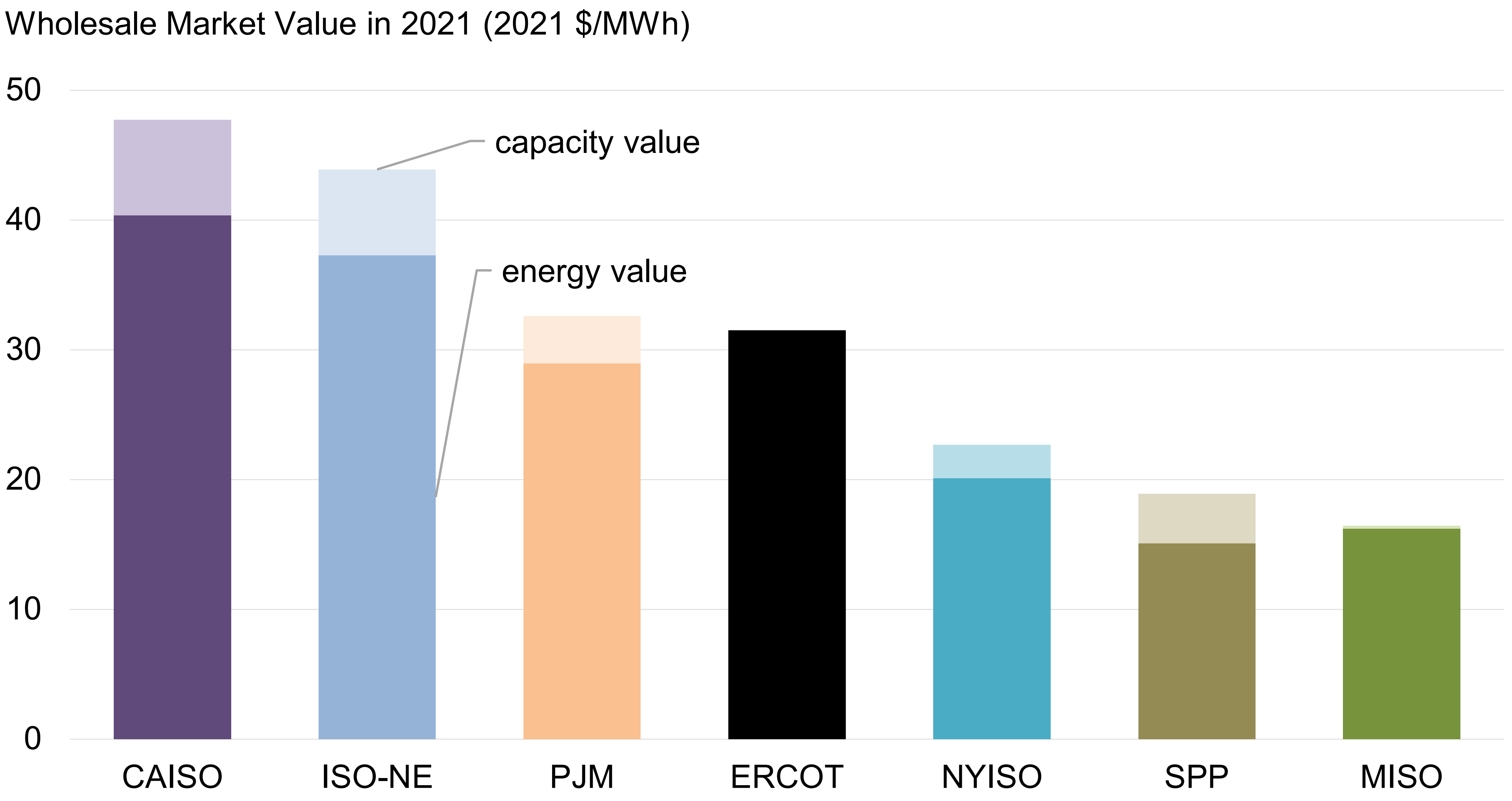


Sources: Berkeley Lab, ABB, ISOs

Wholesale market value considers hourly local wholesale energy price and hourly wind output, along with capacity value where available

Interactive data visualization: https://emp.lbl.gov/wind-energy-market-value

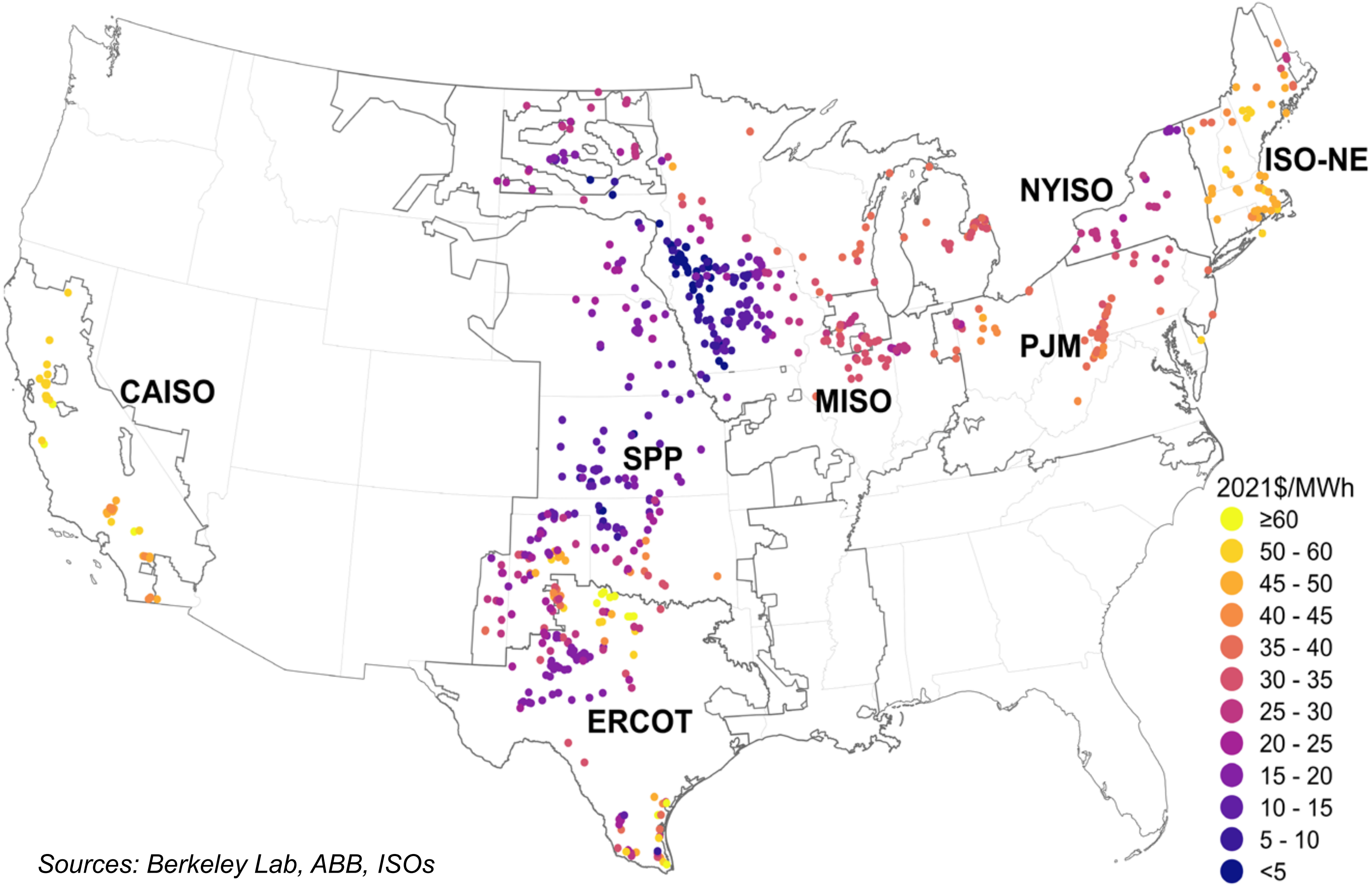
The wholesale market value of wind energy in 2021 varied by region: lowest in MISO, SPP, and NYISO; highest in CAISO



Sources: Berkeley Lab, ABB, ISOs

Interactive data visualization: https://emp.lbl.gov/wind-energy-market-value

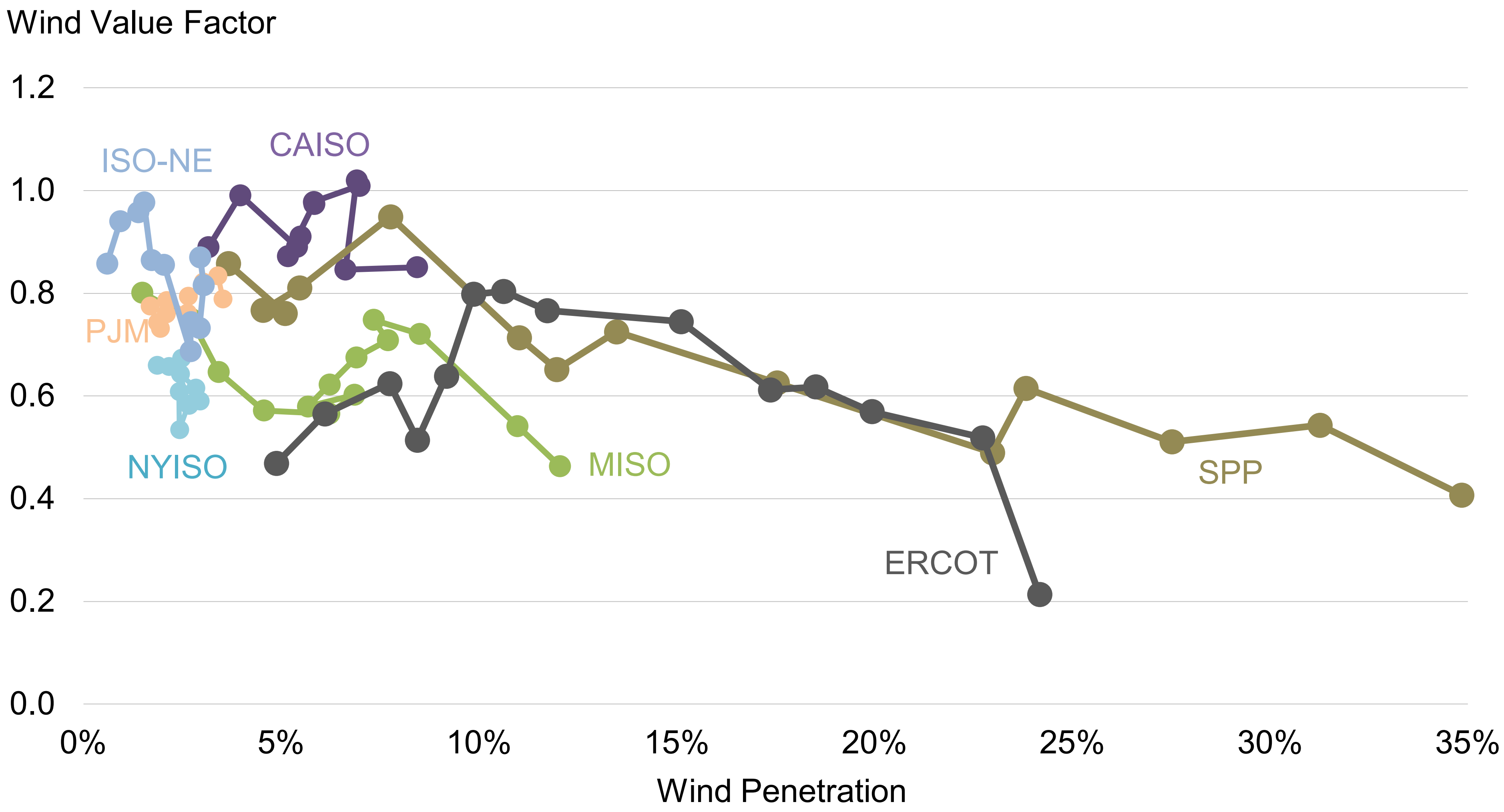
The grid-system market value of wind varies substantially by project location



Sources: Berkeley Lab, ABB, ISOs

Interactive data visualization: https://emp.lbl.gov/wind-energy-market-value

Average “value factor” of wind (value relative to flat block) is highly variable across regions, tends to decline with penetration

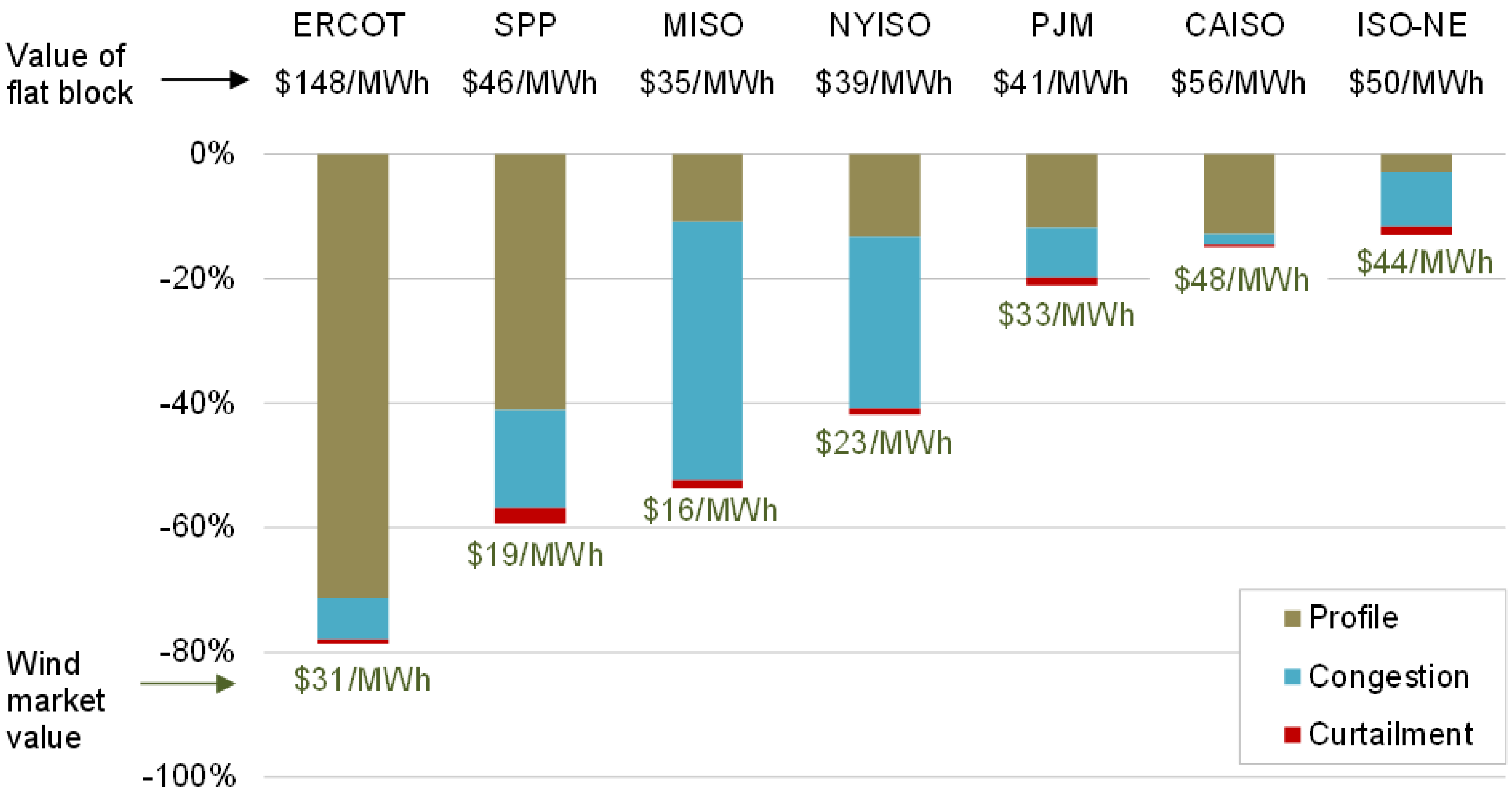


Sources: Berkeley Lab, ABB, ISOs

Value factor = wholesale market value of wind relative to generalized flat block of power in region; generalized flat block is 24x7 average price across all pricing nodes in region

Grid-system market value of wind tends to decline with penetration, impacted by output profile, transmission congestion, and curtailment

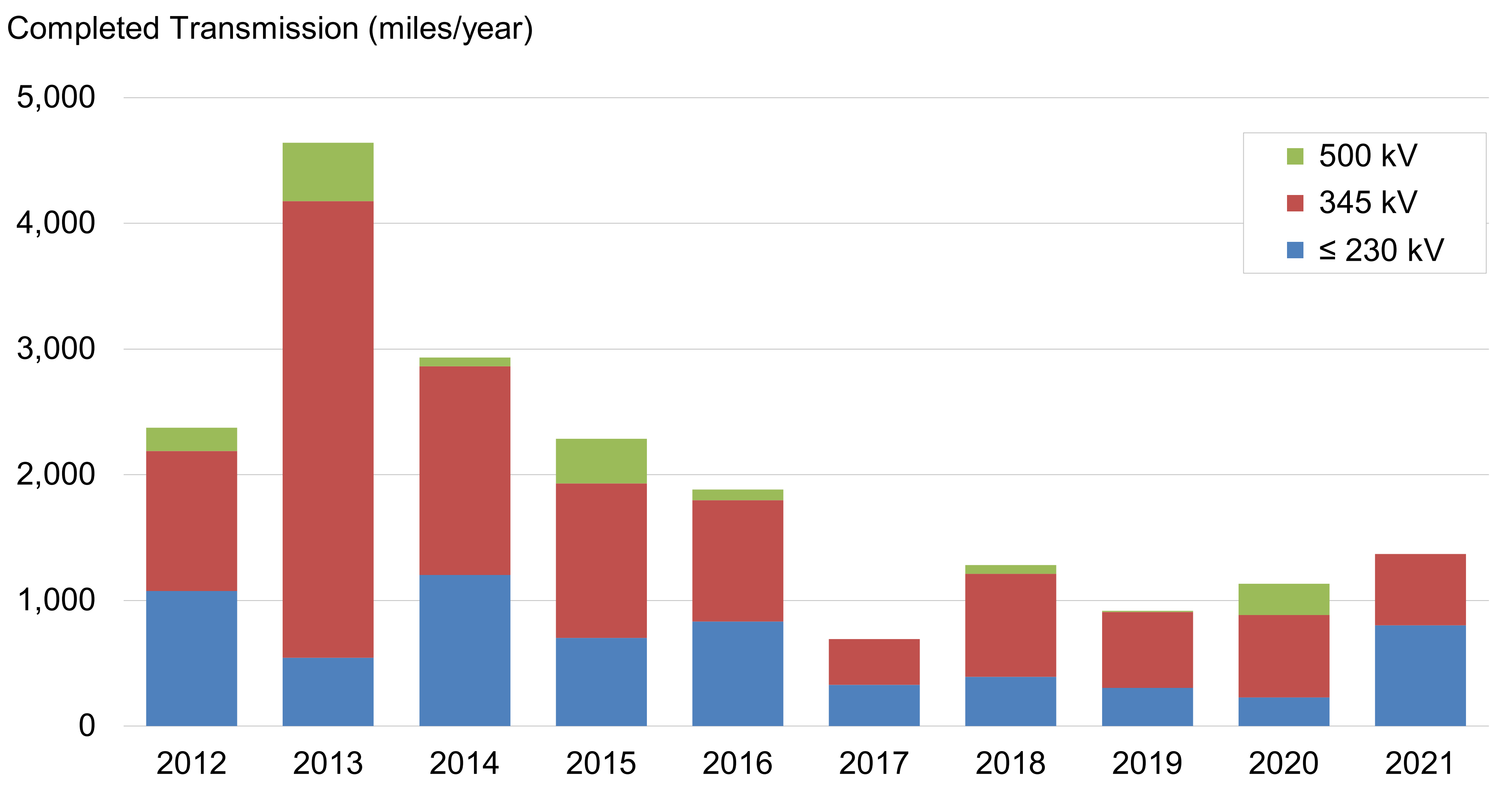
Average market value de-rate of wind in 2021 relative to a flat block varied by region: dominated by wind's output profile in some regions (ERCOT, SPP, PJM, CAISO), and congestion in others (MISO, NYISO, ISO-NE)



Sources: Berkeley Lab, ABB, ISOs

As a location-dependent resource, wind power often requires or benefits from new transmission

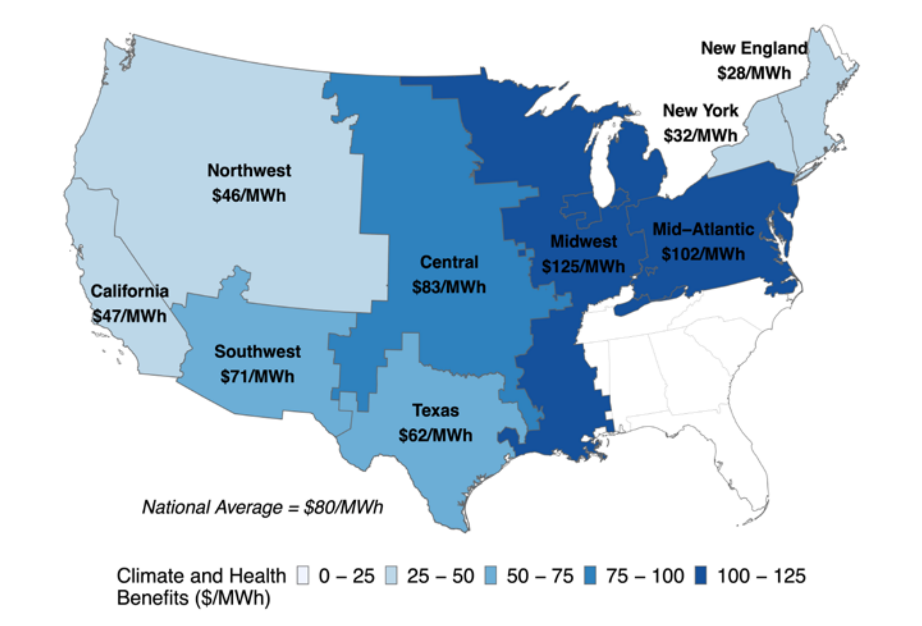
New transmission build has been relatively modest in recent years



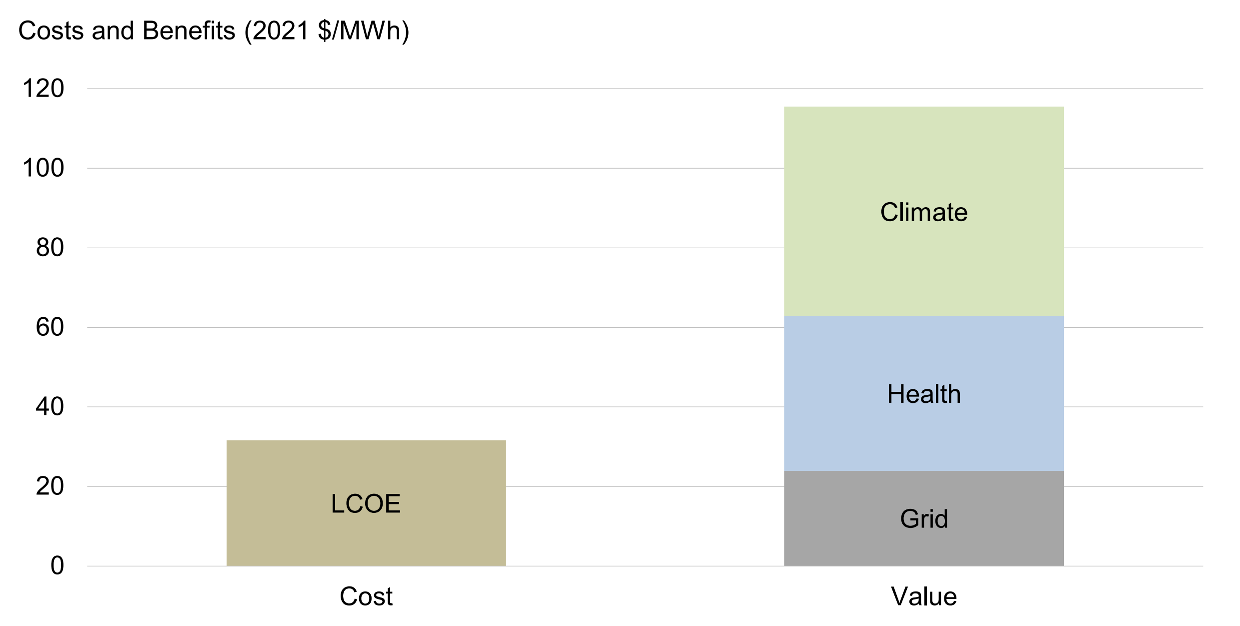
Source: FERC

The health and climate benefits of wind dwarf its grid-system value, and the combination of all three far exceeds the levelized cost of wind

Health and Climate Benefits of Wind in 2021 Vary Regionally, Average $80/MWh Nationally



Grid, Health, and Climate Benefits of New Wind Plants in 2021 Exceed LCOE

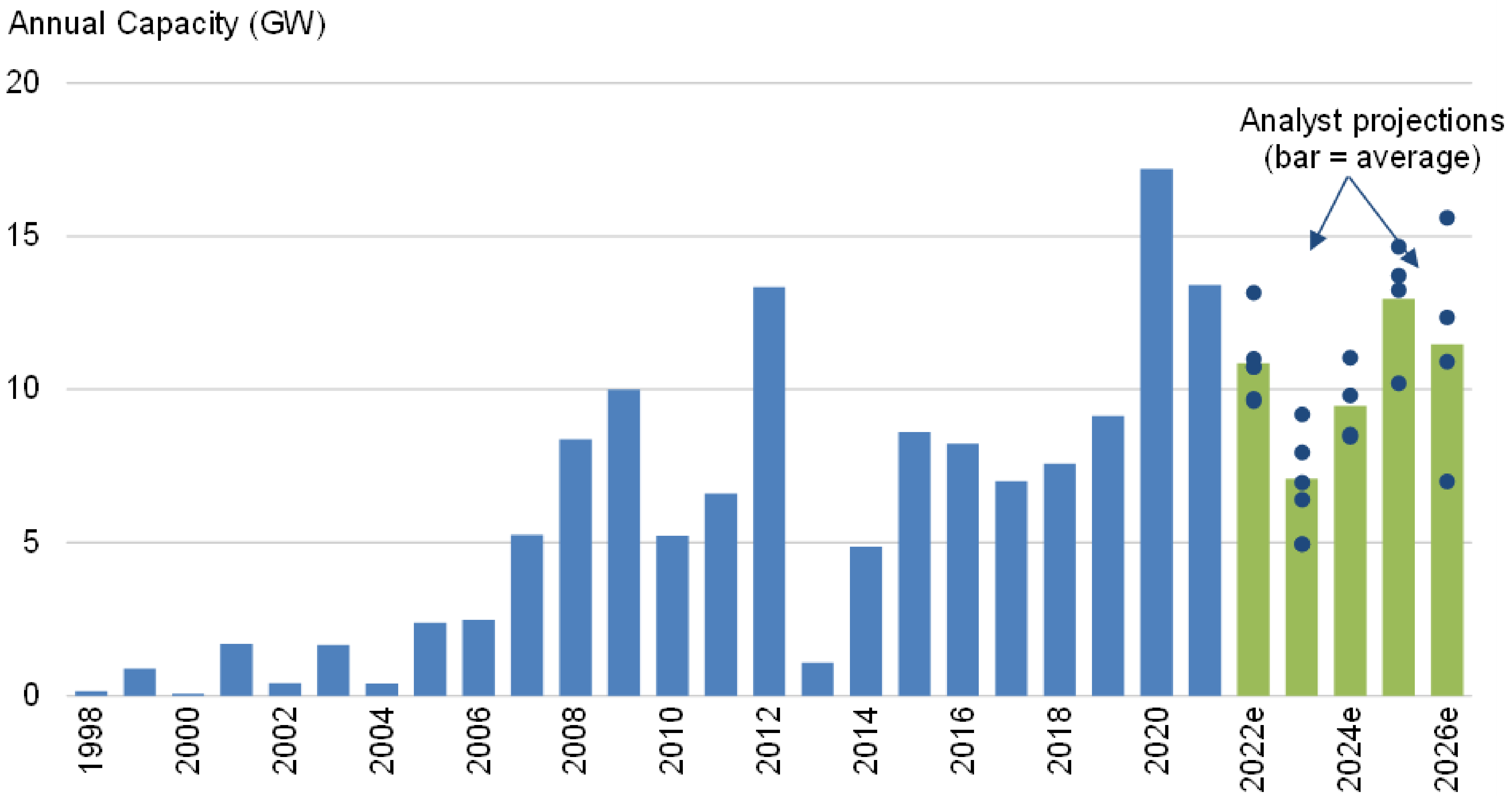


Note: Estimates not provided for Southeast due to small number of wind plants in that region.

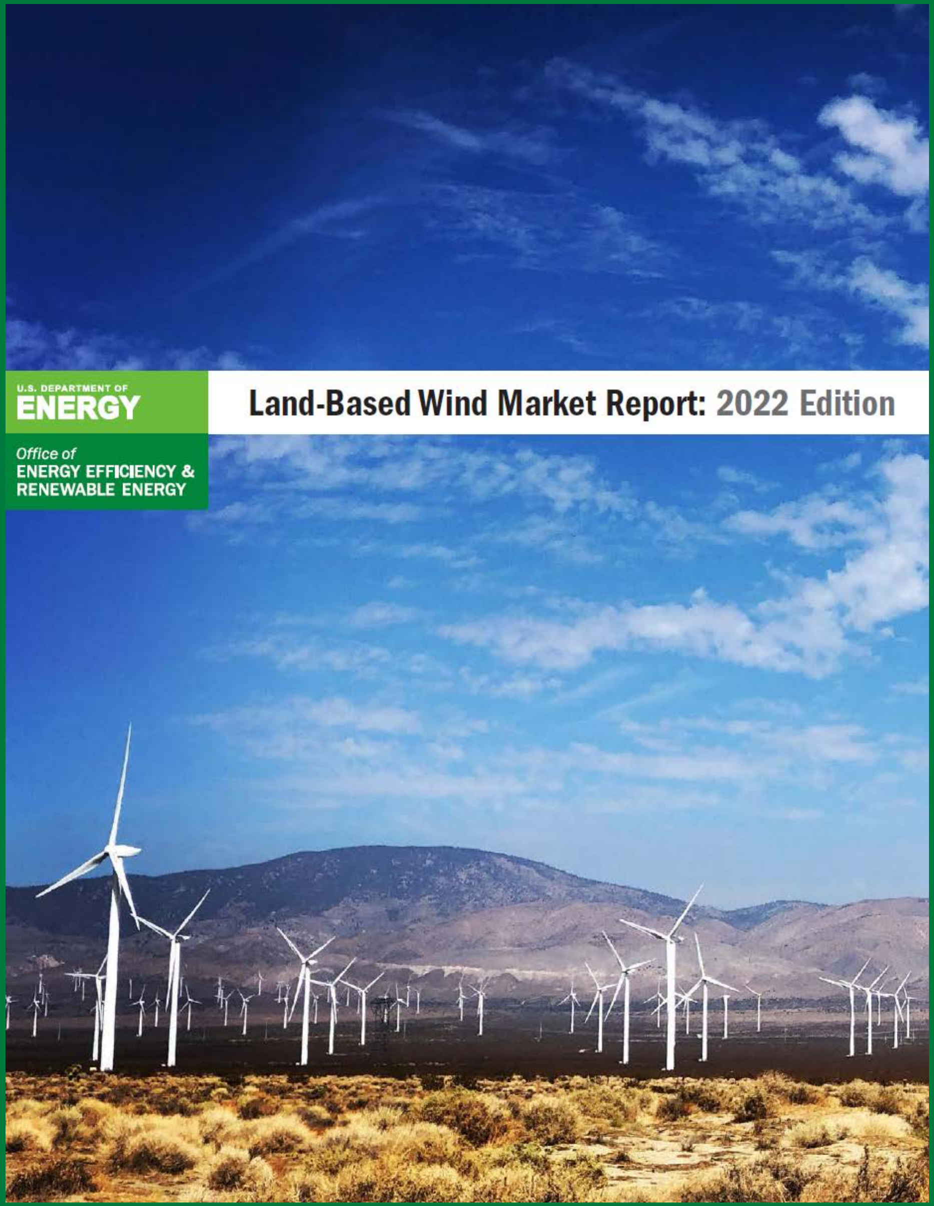
Sources: Berkeley Lab, EIA Form 930, Fell and Johnson (2021)

Future Outlook

Independent analysts anticipate a decline in wind additions over the next couple years, but with a rebound starting in 2024



Sources: ACP, independent analyst projections



The underlying report, an accessible data file, and multiple visualizations can be found at:

- windreport.lbl.gov

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