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Witness: Matthew Langley
Sponsoring Party: Infinity Wind Power
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File No.: EA-2016-0358
Date Testimony Prepared: February 21, 2017

BEFORE THE PUBLIC SERVICE COMMISSION
OF THE STATE OF MISSOURI

In the Matter of the Application of Grain Belt Express Clean Line LLC for a Certificate of Convenience and Necessity Authorizing it to Construct, Own, Operate, Control, Manage and Maintain a High Voltage, Direct Current Transmission Line and an Associated Converter Station Providing an Interconnection on the Maywood - Montgomery 345 kV Transmission Line.	)	File No. EA-2016-0358

CROSS-SURREBUTTAL TESTIMONY OF

MATT LANGLEY

ON BEHALF OF

INFINITY WIND POWER

February 21, 2017

Infinity Exhibit No. 876NP
Date 3.23.17 Reporter TS
File No. EA-2016-0358

NP

I. INTRODUCTION AND PURPOSE OF TESTIMONY

Q. Please state your name.

A. My name is Matt Langley.

Q. Are you the same Matt Langley who filed Rebuttal Testimony in this matter on January 24, 2017?

A. Yes.

Q. What is the purpose of your testimony?

A. The purpose of my testimony is to respond to portions of the rebuttal testimony of Mr. Joseph J. Jaskulski, filed on behalf of Missouri Landowners Alliance, relating to potential users of the Grain Belt Express line, and also the Production Tax Credits (PTCs) for wind development. Additionally, I will respond to the rebuttal testimony of Paul Glenden Justis, Jr., filed on behalf of the Show Me Concerned Landowners, relating to the costs of wind energy in Kansas.

Q. How is your testimony structured?

A. I will first address the testimony of Mr. Jaskulski, and will then address the testimony of Mr. Justis.

II. RESPONSE TO MR. JASKULSKI

Contracts for energy using the Grain Belt Express line

Q. Mr. Jaskulski states, on page five of his rebuttal testimony, that there are no memoranda of understanding or contracts between wind farms and potential load-serving customers in Missouri utilizing the Grain Belt Express line. Do you agree?

A. No, I do not agree. In January, Infinity executed a 20-year power purchase agreement with the Missouri Joint Municipal Electric Utility Commission (MJMEUC). This is a binding contract between Infinity and MJMEUC that will result in the delivery of up to 200MW of wind energy from Infinity's Iron Star Wind Project to MJMEUC's member utilities via the Grain Belt Express. In order to secure performance under the contract, Infinity provided to MJMEUC a significant security payment, which is common under these types of contracts. The security payment is important to note for the Commission because it highlights the seriousness of the contract. Infinity would not have committed the financial resources to secure this competitively sourced contract if it was a free option contract, or in other words, a non-binding contract.

Production Tax Credits

Q. Mr. Jaskulski states, on page thirteen of his rebuttal testimony that the wind farms connecting to the Grain Belt Express will not receive 100% of the PTCs when they are built. Do you agree?

A. No, I disagree with Mr. Jaskulski's conclusion for two reasons. First, while I agree that the IRS' safe harbor provision requires a demonstration of continuous construction for wind farms coming on-line more than four years after the start of construction in 2016, as noted by Mr. Jaskulski, I disagree with Mr. Jaskulski's assertion that none the wind farms connecting to the Grain Belt Express are able to receive the full 100% value of the PTCs. Mr. Jaskulski's interpretation of the rule is a worst-case-scenario and assumes that no wind farms will be able to demonstrate continuous construction under the rule to qualify for receipt of 100% of the PTCs. There is nothing to support this contention. As acknowledged by Mr. Jaskulski, the PTCs are still available after 2020 so long as the developer can document that it is making continuous efforts to complete construction.

The second option for wind developers to receive the full benefit of the PTCs is to bring a windfarm online prior to the end of 2020, thus negating the need to prove or document "continuous efforts". So, for example, in the case of the Grain Belt Express line, a windfarm could be brought online prior to the end of 2020 and operated in the Southwest Power Pool (SPP) market until the Grain Belt Express line is operational.

III. RESPONSE TO MR. JUSTIS

Q. Did you review the testimony and levelized cost of electricity (LCOE) analysis conducted by Mr. Justis?

A. Yes, I read both Mr. Justis' Rebuttal Testimony, and his work papers that are cited in said testimony.

Q. Do you agree with the analysis he discusses on page ten of his testimony?

A. No, I don't believe that Mr. Justis used appropriate assumptions when computing the LCOE depicted in the "Kansas Wind via GBX" column of his Figure 3. First, in looking at Mr. Justis' workpapers, it appears that he overstates the capital cost of building wind in Kansas by over 20%.[1] Industry sources place the cost of wind far below Mr. Justis' assumptions. First, the 2015 Wind Technologies Market Report, published by the Department of Energy (DOE),[2] shows that the capacity-weighted average installed project cost in 2015 is $1,690/kW (see p. 53) as compared to Mr. Justis' *[redacted]*as depicted in his workpapers underlying the values reflected in his Figure 3. I have

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[1] *[redacted]*

[2] https://energy.gov/sites/prod/files/2016/08/f33/2015-Wind-Technologies-Market-Report-08162016.pdf, p. 53.

attached as **Exhibit ML-1(P),** a copy of the Input tab of Mr. Justis' workpaper.[3] For ease of reference, I have also attached a copy of the DOE report as **Exhibit ML-2.**

A recent Kansas project also shows Mr. Justis' $/kW figure is overstated. **Exhibit ML-3** is a 2016 Westar Energy press lease reflecting a 280 megawatt project with a capital investment of approximately $1,554/kW. The $1,554/kW capital cost of the Westar project is consistent with the DOE findings because, as noted on page 56 of the report, the installed cost for projects located in the "Interior" region of the country, which includes Kansas, is below the national average. Both the DOE and the Westar examples highlight the overstatement of Mr. Justis' capital cost assumptions.

Mr. Justis then takes his inflated $/kW number, and increases it by an assumed rate of inflation to project the 2016 costs to 2021 costs, when grossing up his "Base Capital Cost ($/KW)" number to the "Risk Adjusted Capital Cost ($/KW), In-Service Year". While increasing for inflation may normally seem like a reasonable approach when discussing capital investment, the reality in the renewable energy industry is that the installed cost of wind energy facilities has fallen every year since 2009, as noted on page 52-53 of Exhibit ML-2. When noting the DOE $/kW, the $/kW of the recent Westar project in Kansas, and coupling those values with the downward trend of the average installed project costs reflected in the DOE report, it is clear that Mr. Justis' $/kW assumption is outside the industry norm. Adding his inflation assumption to the already excessive $/kW value further exacerbates the errors in his assumptions.[4] A reasonable analysis would at a minimum hold today's costs constant, or more

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[3] GJustis GBX Testimony Support Calcs (HC). Mr. Justis' workpapers and testimony were originally provided as HC, but were later revised to Proprietary after discussions with counsel for Grain Belt Express, Show Me, and Infinity.

[4] https://energy.gov/sites/prod/files/2016/08/f33/2015-Wind-Technologies-Market-Report-08162016.pdf, p. 52.

appropriately, continue to project a decline in capital costs for wind development projects, yet Mr. Justis' approach does the opposite.

Further, Mr. Justis also overstates the fixed O&M costs for wind farms, which is further supported on page 60 of the DOE report. Mr. Justis assumes a fixed annual O&M cost of *[redacted]* yet the DOE reflects an O&M cost of around $25.50/kW, from EDPR, who is one of the largest and most respected operators in the industry.

Finally, in his workpapers, as seen in the entry labeled "Production Tax Credit %" in Exhibit ML-1, Mr. Justis also incorrectly assumes that the wind projects that would interconnect into the Grain Belt Express would only be able to take advantage of *[redacted]* of the value of the Federal PTCs, an erroneous assumption that I previously discussed in response to Mr. Jaskulski.

The result of Mr. Justis' faulty assumptions is an LCOE for wind that is almost an order of magnitude higher than what respected industry publications have published in the last few years.

Q. What other support can you lend to your claim of a lower cost of energy?

A. Certainly the most compelling support is found in the executed Power Purchase Agreement between Infinity and MJMEUC which reflects a price of *[redacted]* This is clearly a much lower price than Mr. Justis' assumed cost of *[redacted]*[5] Furthermore, page 62 of the DOE report shows

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[5] *[redacted]*

that the PPAs being signed in the Interior region are consistently below the *[redacted]* price that Mr. Justis articulates, which would suggest that Infinity's price is by no means out of market.

Q. Does this conclude your testimony?

A. Yes.

AFFIDAVIT

STATE OF CALIFORNIA)
) ss
COUNTY OF ALAMEDA)

I, Matthew Langley, upon oath first duly sworn, state that I am Vice President, Finance and Origination of Infinity Wind Power, that I am authorized to make this Affidavit on behalf of Infinity Wind Power, that I have prepared the foregoing *Cross-Surrebuttal Testimony*, and that the statements contained therein are true and correct to the best of my knowledge and belief.

Matthew Langley
Vice President, Finance and Origination
Infinity Wind Power

Subscribed and sworn to before me this 21 day of February, 2017.

ERICH MASON HARRIS
Commission # 2072429
Notary Public - California
Alameda County
My Comm. Expires Jun 23, 2018

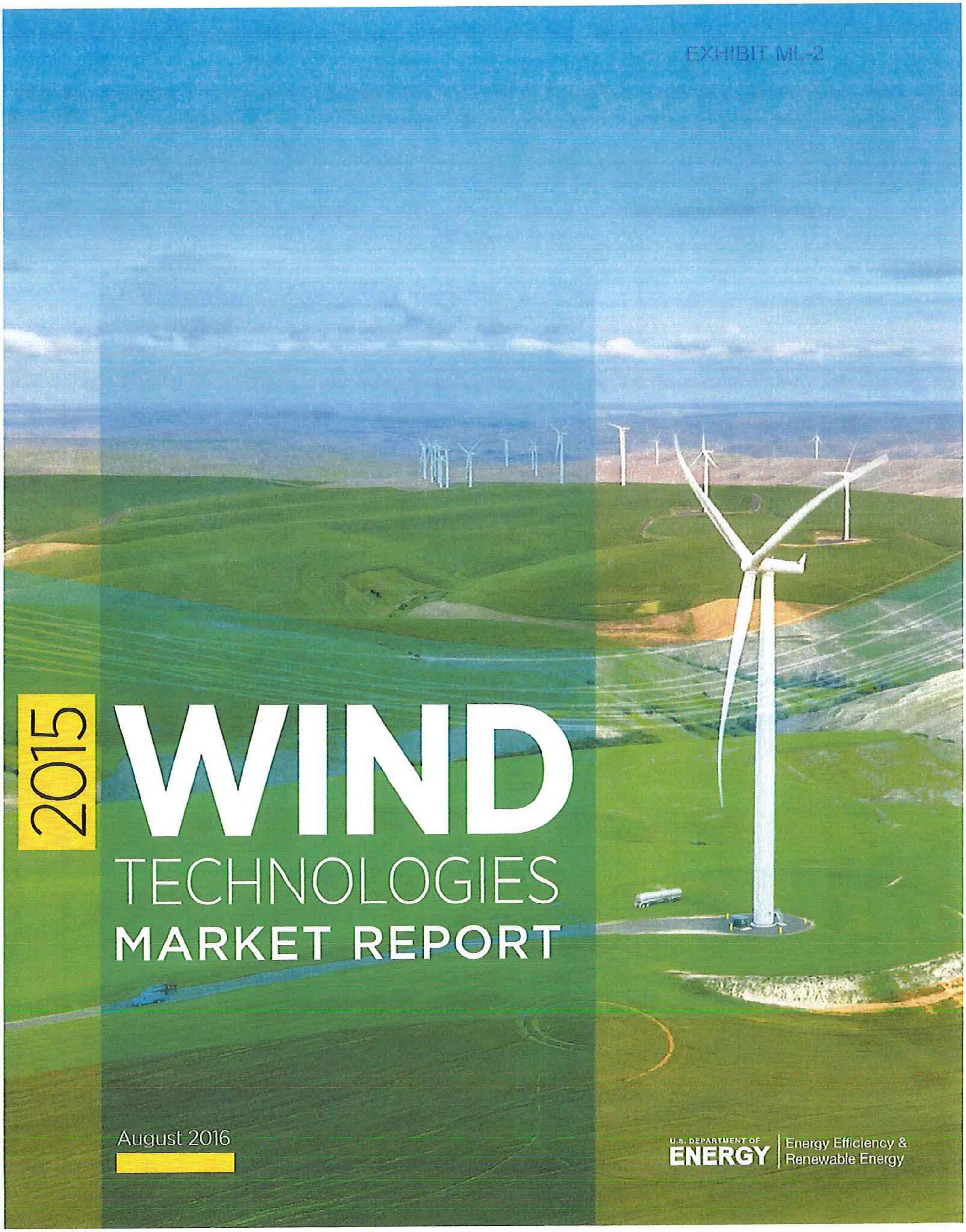
Erich Mason Harris
Notary Public

My appointment expires: June 23, 2018

EXHIBIT ML-1 (NP)

[redacted]

EXHIBIT ML-2



2015 WIND TECHNOLOGIES MARKET REPORT

August 2016

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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 external review, the study benefited from the advice and comments of six wind industry and trade association representatives, two utility-sector representatives, three federal laboratory staff, and four U.S. government employees and contractors.

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2015 Wind Technologies Market Report

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Acknowledgments

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Acronyms and Abbreviations

AWEA	American Wind Energy Association
Bloomberg NEF	Bloomberg New Energy Finance
BPA	Bonneville Power Administration
BOEM	Bureau of Ocean Energy Management
CAISO	California Independent System Operator
DOE	U.S. Department of Energy
EDPR	EDP Renováveis
EEI	Edison Electric Institute
EIA	U.S. Energy Information Administration
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
GE	General Electric Corporation
GW	gigawatt
HTS	Harmonized Tariff Schedule
ICE	Intercontinental Exchange
IOU	investor-owned utility
IPP	independent power producer
ISO	independent system operator
ISO-NE	New England Independent System Operator
ITC	investment tax credit
kV	kilovolt
kW	kilowatt
kWh	kilowatt-hour
m^2	square meter
MISO	Midcontinent Independent System Operator
MW	megawatt
MWh	megawatt-hour
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
NYISO	New York Independent System Operator
O&M	operations and maintenance
OEM	original equipment manufacturer
PJM	PJM Interconnection
POU	publicly owned utility
PPA	power purchase agreement
PTC	production tax credit
REC	renewable energy certificate
RGGI	Regional Greenhouse Gas Initiative
RPS	renewables portfolio standard

RTO	regional transmission organization
SPP	Southwest Power Pool
USITC	U.S. International Trade Commission
W	watt
WAPA	Western Area Power Administration

Executive Summary

Annual wind power capacity additions in the United States surged in 2015 and are projected to continue at a rapid clip in the coming five years. Recent and projected near-term growth is supported by the industry's primary federal incentive—the production tax credit (PTC)—as well as a myriad of state-level policies. Wind additions are also being driven by improvements in the cost and performance of wind power technologies, yielding low power sales prices for utility, corporate, and other purchasers. At the same time, the prospects for growth beyond the current PTC cycle remain uncertain: growth could be blunted by declining federal tax support, expectations for low natural gas prices, and modest electricity demand growth.

Key findings from this year's *Wind Technologies Market Report* include:

Installation Trends

- **Wind power additions surged in 2015, with 8,598 MW of new capacity added in the United States and $14.5 billion invested.** Supported by favorable tax policy and other drivers, cumulative wind power capacity grew by 12%, bringing the total to 73,992 MW.
- **Wind power represented the largest source of U.S. electric-generating capacity additions in 2015.** Wind power constituted 41% of all U.S. generation capacity additions in 2015, up sharply from its 24% market share the year before and close to its all-time high. Over the last decade, wind power represented 31% of all U.S. capacity additions, and an even larger fraction of new generation capacity in the Interior (54%) and Great Lakes (48%) regions. Its contribution to generation capacity growth over the last decade is somewhat smaller in the West (22%) and Northeast (21%), and considerably less in the Southeast (2%).
- **The United States ranked second in annual wind additions in 2015, but was well behind the market leaders in wind energy penetration.** A record high amount of new wind capacity, roughly 63,000 MW, was added globally in 2015, yielding a cumulative total of 434,000 MW. The United States remained the second-leading market in terms of cumulative capacity, but was the leading country in terms of wind power production. A number of countries have achieved high levels of wind penetration; end-of-2015 wind power capacity is estimated to supply the equivalent of roughly 40% of Denmark's electricity demand, and between 20% to 30% of Portugal, Ireland, and Spain's demand. In the United States, the wind power capacity installed by the end of 2015 is estimated, in an average year, to equate to 5.6% of electricity demand.
- **Texas installed the most capacity in 2015 with 3,615 MW, while twelve states meet or exceed 10% wind energy penetration.** New utility-scale wind turbines were installed in 20 states in 2015. On a cumulative basis, Texas remained the clear leader, with 17,711 MW. Notably, the wind power capacity installed in Iowa and South Dakota supplied more than 31% and 25%, respectively, of all in-state electricity generation in 2015, with Kansas close behind at nearly 24%. A total of twelve states have achieved wind penetration levels of 10% or higher.
- **The first commercial offshore turbines are expected to be commissioned in the United States in 2016 amid mixed market signals.** At the end of 2015, global offshore wind capacity stood at roughly 12 GW. In the United States, the 30 MW Block Island project off

the coast of Rhode Island will be the first plant to be commissioned, anticipated by the end of 2016. Projects in Massachusetts, New Jersey, Virginia, and Oregon, meanwhile, all experienced setbacks. Strides continued to be made in the federal arena in 2015, both through the U.S. Department of the Interior's responsibilities in issuing offshore leases, and the U.S. Department of Energy's (DOE's) funding for demonstration projects. A total of 23 offshore wind projects totaling more than 16 GW are in various stages of development in the United States.

- **Data from interconnection queues demonstrate that a substantial amount of wind power capacity is under consideration.** At the end of 2015, there were 110 GW of wind power capacity within the transmission interconnection queues reviewed for this report, representing 31% of all generating capacity within these queues—higher than all other generating sources except natural gas. In 2015, 45 GW of wind power capacity entered interconnection queues (the largest annual sum since 2010), compared to 58 GW of natural gas and 24 GW of solar.

Industry Trends

- **GE and Vestas captured 73% of the U.S. wind power market in 2015.** Continuing their recent dominance as the three largest turbine suppliers to the U.S., in 2015 GE captured 40% of the market, followed by Vestas (33%) and Siemens (14%). Globally, Goldwind and Vestas were the top two suppliers, followed by GE, Siemens, and Gamesa. Chinese manufacturers continued to occupy positions of prominence in the global ratings, with five of the top 10 spots; to date, however, their growth has been based almost entirely on sales in China.
- **The manufacturing supply chain continued to adjust to swings in domestic demand for wind equipment.** With growth in the U.S. market, wind sector employment reached a new high of 88,000 full-time workers at the end of 2015. Moreover, the profitability of turbine suppliers has rebounded over the last three years. Although there have been a number of recent plant closures, each of the three major turbine manufacturers serving the U.S. market has one or more domestic manufacturing facilities. Domestic nacelle assembly capability stood at roughly 10 GW in 2015, and the United States also had the capability to produce approximately 7 GW of blades and 6 GW of towers annually. Despite the significant growth in the domestic supply chain over the last decade, conflicting pressures remain, such as: an upswing in near- to medium-term expected growth, but also strong international competitive pressures and possible reduced demand over time as the PTC is phased down. As a result, though many manufacturers increased the size of their U.S. workforce in 2015, expectations for significant supply-chain expansion have become more pessimistic.
- **Domestic manufacturing content is strong for some wind turbine components, but the U.S. wind industry remains reliant on imports.** The U.S. is reliant on imports of wind equipment from a wide array of countries, with the level of dependence varying by component. Domestic content is highest for nacelle assembly (>85%), towers (80-85%), and blades and hubs (50-70%), but is much lower (<20%) for most components internal to the nacelle. Exports of wind-powered generating sets from the United States rose from $16 million in 2007 to $544 million in 2014, but fell to $149 million in 2015.
- **The project finance environment remained strong in 2015.** Spurred on by the December 2014 and March 2015 single-year extensions of the PTC's construction start deadline and

IRS safe harbor guidance, respectively, the U.S. wind market raised ~$6 billion of new tax equity in 2015—the largest single-year amount on record. Debt finance increased slightly to $2.9 billion, with plenty of additional availability. Tax equity yields drifted slightly lower to just below 8% (in unlevered, after-tax terms), while the cost of term debt fell to just 4% by the end of the year—perhaps the lowest it has ever been. Looking ahead, 2016 should be another busy year, given the recent 5-year PTC extension and phase down.

- **IPPs own the vast majority of wind assets built in 2015.** Independent power producers (IPPs) own 85% of the new wind capacity installed in the United States in 2015, with the remaining assets owned by investor-owned utilities (12%) and other entities (3%). On a cumulative basis through 2015, IPPs own 83% and utilities own 15% of U.S. wind capacity, with the remaining 2% owned by entities that are neither IPPs nor utilities (e.g., towns, schools, businesses, farmers).
- **Long-term contracted sales to utilities remained the most common off-take arrangement, but direct retail sales gained ground.** Electric utilities continued to be the dominant off-takers of wind power in 2015, either owning (12%) or buying (48%) power from 60% of the new capacity installed last year. Merchant/quasi-merchant projects accounted for another 29%, while direct retail purchasers – including corporate off-takers – are buying the remaining 10% (a share that should increase next year). On a cumulative basis, utilities own (15%) or buy (53%) power from 68% of all wind capacity in the United States, with merchant/quasi-merchant projects accounting for 24%, power marketers 6%, and direct retail buyers just 2% (though likely to increase in the coming years).

Technology Trends

- **Turbine nameplate capacity, hub height, and rotor diameter have all increased significantly over the long term.** The average nameplate capacity of newly installed wind turbines in the United States in 2015 was 2.0 MW, up 180% since 1998–1999. The average hub height in 2015 was 82.0 meters, up 47% since 1998-1999, while the average rotor diameter was 102 meters, up 113% since 1998–1999.
- **Growth in rotor diameter has outpaced growth in nameplate capacity and hub height in recent years.** Rotor scaling has been especially significant in recent years, and more so than increases in nameplate capacity and hub heights, both of which have seen a stabilization of the long-term trend since at least 2011. In 2008, no turbines employed rotors that were 100 meters in diameter or larger; by 2015, 86% of new installed wind capacity featured rotor diameters of at least 100 meters.
- **Turbines originally designed for lower wind speed sites have rapidly gained market share.** With growth in average swept rotor area outpacing growth in average nameplate capacity, there has been a decline in the average "specific power" [i] (in W/m^2) over time, from 394 W/m^2 among projects installed in 1998–1999 to 246 W/m^2 among projects installed in 2015. In general, turbines with low specific power were originally designed for lower wind speed sites. Another indication of the increasing prevalence of lower wind speed turbines is that, in 2015, the vast majority of new installations used IEC Class 3 and Class 2/3 turbines.

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[i] 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.

- **Turbines originally designed for lower wind speeds are now regularly employed in both lower and higher wind speed sites; taller towers predominate in the Great Lakes and Northeast.** Low specific power and IEC Class 3 and 2/3 turbines are now regularly employed in all regions of the United States, and in both lower and higher wind speed sites. In parts of the Interior region, in particular, relatively low wind turbulence has allowed turbines designed for lower wind speeds to be deployed across a wide range of site-specific resource conditions. The tallest towers, meanwhile, have principally been deployed in the Great Lakes and Northeastern regions, in lower wind speed sites, with specific location decisions likely driven by the wind shear of the site.

Performance Trends

- **Sample-wide capacity factors have gradually increased, but have been impacted by curtailment and inter-year wind resource variability.** Wind project capacity factors have generally increased over time. For a large sample of projects built from 1998 through 2014, capacity factors averaged 32.8% between 2011 and 2015 versus 31.8% between 2006 and 2010 versus 30.3% between 2000 and 2005. That being said, time-varying influences—such as inter-year variations in the strength of the wind resource or changes in the amount of wind energy curtailment—have partially masked the positive influence of turbine scaling on capacity factors. For example, wind speeds throughout the interior and western U.S. were significantly below normal for much of 2015, which negatively impacted fleet-wide capacity factors. Positively, the degree of wind curtailment has declined recently in what historically have been the most problematic areas. For example, only 1.0% of all wind generation within ERCOT was curtailed in 2015, down sharply from the peak of 17% in 2009.
- **The impact of technology trends on capacity factor becomes more apparent when parsed by project vintage.** Focusing only on performance in 2015 (to partially control for time-varying influences) and parsing capacity factors by project vintage tells a more interesting story, wherein rotor scaling over the past few years has clearly begun to drive capacity factors higher. The average 2015 capacity factor among projects built in 2014 reached 41.2%, compared to an average of 31.2% among projects built from 2004–2011 and just 25.8% among projects built from 1998–2003. The ongoing decline in specific power has been offset to some degree by a trend—especially from 2009 to 2012—towards building projects at lower-quality wind sites. Controlling for these two competing influences confirms this offsetting effect and shows that turbine design changes are driving capacity factors significantly higher over time among projects located within given wind resource regimes. Performance degradation over time is a final driver examined in this section: though many caveats are in order, older wind projects appear to suffer from performance degradation, particularly as they approach and enter their second decade of operations.
- **Regional variations in capacity factors reflect the strength of the wind resource and adoption of new turbine technology.** Based on a sub-sample of wind projects built in 2014, average capacity factors in 2015 were the highest in the Interior region (42.7%). Not surprisingly, the regional rankings are roughly consistent with the relative quality of the wind resource in each region, and they reflect the degree to which each region has adopted turbines with lower specific power or taller towers. For example, the Great Lakes has thus far adopted these new designs to a much larger extent than has the West, with corresponding implications for average capacity factors in each region.

Cost Trends

- **Wind turbine prices remained well below levels seen several years ago.** After hitting a low of roughly $750/kW from 2000 to 2002, average turbine prices increased to more than $1,500/kW by the end of 2008. Wind turbine prices have since dropped substantially, despite increases in hub heights and especially rotor diameters. Recently announced transactions feature pricing in the $850–$1,250/kW range. These price reductions, coupled with improved turbine technology, have exerted downward pressure on project costs and wind power prices.
- **Lower turbine prices have driven reductions in reported installed project costs.** The capacity-weighted average installed project cost within our 2015 sample stood at roughly $1,690/kW—down $640/kW from the apparent peak in average reported costs in 2009 and 2010. Early indications from a preliminary sample of projects currently under construction and anticipating completion in 2016 suggest no material change in installed costs in 2016.
- **Installed costs differed by project size, turbine size, and region.** Installed project costs exhibit some economies of scale, at least at the lower end of the project and turbine size range. Additionally, among projects built in 2015, the windy Interior region of the country was the lowest-cost region, with a capacity-weighted average cost of $1,640/kW.
- **Operations and maintenance costs varied by project age and commercial operations date.** Despite limited data availability, it appears that projects installed over the past decade have, on average, incurred lower operations and maintenance (O&M) costs than older projects in their first several years of operation, and that O&M costs increase as projects age.

Wind Power Price Trends

- **Wind PPA prices remain very low.** After topping out at nearly $70/MWh for PPAs executed in 2009, the national average level-through price of wind PPAs within the Berkeley Lab sample has dropped to around the $20/MWh level, inclusive of the federal production tax credit (PTC), though this latest nationwide average is admittedly focused on a sample of projects that largely hail from the lowest-priced Interior region of the country, where most of the new capacity built in recent years is located. Focusing only on the Interior region, the PPA price decline has been more modest, from ~$55/MWh among contracts executed in 2009 to ~$20/MWh today. Today's low PPA prices have been enabled by the combination of higher capacity factors, declining costs, and record-low interest rates documented elsewhere in this report.
- **The relative economic competitiveness of wind power declined in 2015 with the drop in wholesale power prices.** A sharp drop in wholesale power prices in 2015 made it somewhat harder for wind power to compete, notwithstanding the low wind energy PPA prices available to purchasers. This is particularly true in light of the continued expansion of wind development in the Interior region of the U.S., where wholesale power prices are among the lowest in the nation. That said, the price stream of wind PPAs executed in 2014-2016 compares very favorably to the EIA's latest projection of the fuel costs of gas-fired generation extending out through 2040.

Policy and Market Drivers

- **A long-term extension and phase down of federal incentives for wind projects is leading to a resurgent domestic market.** In December 2015, Congress passed a 5-year phased-down extension of the PTC. To qualify, projects must begin construction before January 1, 2020. In May 2016, the IRS issued favorable guidance allowing four years for project completion after the start of construction, without the burden of having to prove continuous construction. In extending the PTC, Congress also included a progressive reduction in the value of the credit for projects starting construction after 2016. Specifically, the PTC will phase down in increments of 20 percentage points per year for projects starting construction in 2017 (80% PTC), 2018 (60%), and 2019 (40%).
- **State policies help direct the location and amount of wind power development, but current policies cannot support continued growth at recent levels.** As of July 2016, RPS policies existed in 29 states and Washington D.C. Of all wind capacity built in the United States from 2000 through 2015, roughly 51% is delivered to load-serving entities with RPS obligations. Among just those wind projects built in 2015, however, this proportion fell to 24%. Existing RPS programs are projected to require average annual renewable energy additions of roughly 3.7 GW/year through 2030, only a portion of which will come from wind. These additions are well below the average growth rate in wind power capacity in recent years.
- **System operators are implementing methods to accommodate increased penetrations of wind energy, but transmission and other barriers remain.** Studies show that wind energy integration costs are almost always below $12/MWh—and often below $5/MWh—for wind power capacity penetrations of up to or even exceeding 40% of the peak load of the system in which the wind power is delivered. System operators and others continue to implement a range of methods to accommodate increased wind energy penetrations and reduce barriers to deployment: treating wind as dispatchable, increasing wind's capability to provide grid services, revising ancillary service market design, balancing area coordination, and new transmission investment. About 1,500 miles of transmission lines came on-line in 2015—less than in previous years. The wind industry, however, has identified 15 near-term transmission projects that—if all were completed—could carry 52 GW of additional wind capacity.

Future Outlook

With the five-year phased-down extension of the PTC, annual wind power capacity additions are projected to continue at a rapid clip for several years. Near-term additions will also be driven by improvements in the cost and performance of wind power technologies, which continue to yield very low power sales prices. Growing corporate demand for wind energy and state-level policies are expected to play important roles as well, as might utility action to proactively stay ahead of possible future environmental compliance obligations. As a result, various forecasts for the domestic market show expected capacity additions averaging more than 8,000 MW/year from 2016 to 2020. Projections for 2021 to 2023, however, show a downturn in additions as the PTC progressively delivers less value to the sector. Expectations for continued low natural gas prices, modest electricity demand growth, and lower near-term demand from state RPS policies also put a damper on growth expectations, as do inadequate transmission infrastructure and competition from solar energy in certain regions of the country. At the same time, the potential for continued technological advancements and cost reductions enhance the prospects for longer-term growth, as does burgeoning corporate demand for wind energy and longer-term state RPS requirements. EPA's Clean Power Plan, depending on its ultimate fate, may also create new markets for wind. Moreover, new transmission in some regions is expected to open up high-quality wind resources to development. Given these diverse underlying potential trends, wind capacity additions—especially after 2020—remain uncertain.

1. Introduction

Annual wind power capacity additions in the United States surged in 2015 and are projected to continue at a rapid clip in the coming five years. Recent and projected near-term growth is supported by the industry's primary federal incentive—the production tax credit (PTC)—having been extended for several years (though with a phase-down schedule, described further on pages 68-69), as well as a myriad of state-level policies. Wind additions are also being driven by improvements in the cost and performance of wind power technologies, yielding low power sales prices for utility, corporate, and other purchasers. At the same time, the prospects for growth beyond the current PTC cycle remain uncertain: growth could be blunted by declining federal tax support, expectations for low natural gas prices, and modest electricity demand growth.

This annual report—now in its tenth year—provides a detailed overview of developments and trends in the U.S. wind power market, with a particular focus on 2015. The report begins with an overview of key installation-related trends: trends in U.S. wind power capacity growth; how that growth compares to other countries and generation sources; the amount and percentage of wind energy in individual states; the status of offshore wind power development; and the quantity of proposed wind power capacity in various interconnection queues in the United States. Next, the report covers an array of wind power industry trends: developments in turbine manufacturer market share; manufacturing and supply-chain developments; wind turbine and component imports into and exports from the United States; project financing developments; and trends among wind power project owners and power purchasers. The report then turns to a summary of wind turbine technology trends: turbine size, hub height, rotor diameter, specific power, and IEC Class. After that, the report discusses wind power performance, cost, and pricing trends. In so doing, it describes trends in project performance, wind turbine transaction prices, installed project costs, and operations and maintenance (O&M) expenses. It also reviews the prices paid for wind power in the United States and how those prices compare to short-term wholesale electricity prices and forecasts of future natural gas prices. Next, the report examines policy and market factors impacting the domestic wind power market, including federal and state policy drivers as well as transmission and grid integration issues. The report concludes with a preview of possible near-term market developments.

This edition of the annual report updates data presented in previous editions while highlighting key trends and important new developments from 2015. The report concentrates on larger, utility-scale wind turbines, defined here as individual turbines that *exceed* 100 kW in size.[1] The U.S. wind power sector is multifaceted, however, and also includes smaller, customer-sited wind turbines used to power residences, farms, and businesses. Further information on *distributed wind power*, which includes smaller wind turbines as well as the use of larger turbines in distributed applications, is available through a separate annual report funded by the U.S. Department of Energy (DOE).[2] Additionally, because this report has an historical focus, and all

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[1] This 100-kW threshold between "smaller" and "larger" wind turbines is applied starting with 2011 projects to better match AWEA's historical methodology, and is also justified by the fact that the U.S. tax code makes a similar distinction. In years prior to 2011, different cut-offs are used to better match AWEA's reported capacity numbers and to ensure that older utility-scale wind power projects in California are not excluded from the sample.

[2] As used by the DOE, distributed wind is defined in terms of technology application based on a wind project's location relative to end use and power distribution infrastructure, rather than on technology size or project size. Distributed wind systems are connected either on the customer side of the meter (to meet the onsite load) or directly

U.S. wind power projects have been land-based, its treatment of trends in the offshore wind power sector is limited to a brief summary of recent developments.

Much of the data included in this report were compiled by Lawrence Berkeley National Laboratory (Berkeley Lab) from a variety of sources, including the American Wind Energy Association (AWEA), the U.S. Energy Information Administration (EIA), and the Federal Energy Regulatory Commission (FERC). The Appendix provides a summary of the many data sources used in the report, and a list of specific references follows the Appendix. Data on wind power capacity additions in the United States (as well as wind power projects) are based largely on information provided by AWEA, although minor methodological differences may yield slightly different numbers from AWEA (2016a) in some cases. In other cases, the data shown here represent only a sample of actual wind power projects installed in the United States; furthermore, the data vary in quality. As such, emphasis should be placed on overall trends, rather than on individual data points. Finally, each section of this document primarily focuses on historical market information, with an emphasis on 2015. With some limited exceptions—including the final section of the report—the report does not seek to forecast trends.

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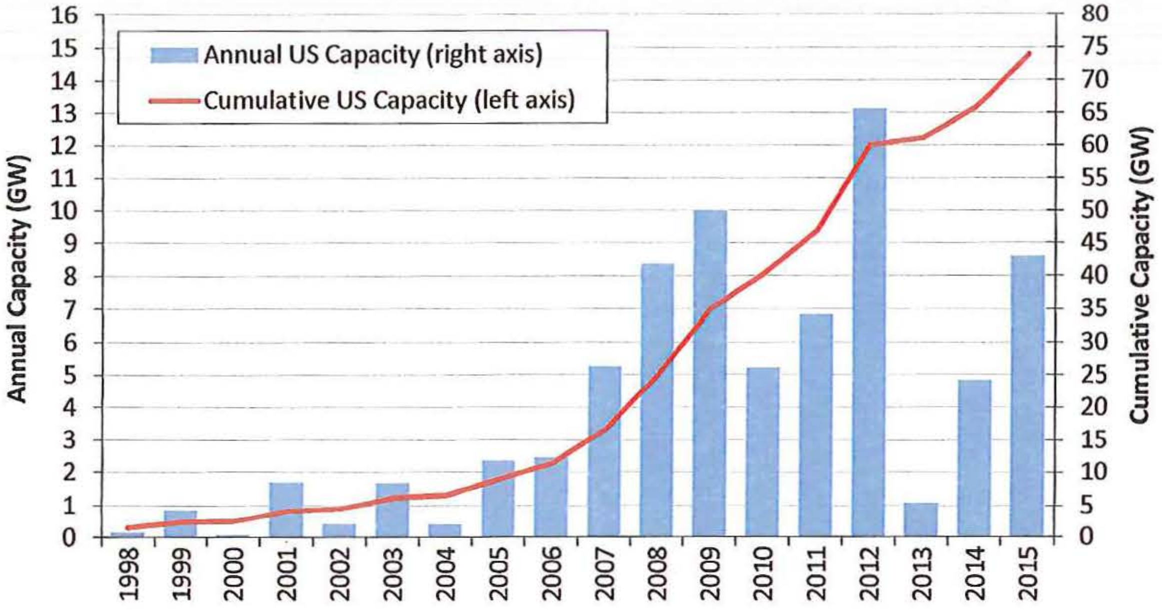
to the local grid (to support grid operations or offset large loads nearby). For the DOE distributed wind report, see: Orrell and Foster (2016).

2. Installation Trends

Wind power additions surged in 2015, with 8,598 MW of new capacity added in the United States and $14.5 billion invested

The U.S. wind power market surged in 2015, with 8,598 MW of new capacity added, bringing the cumulative total to 73,992 MW (Figure 1).[3] This growth required $14.5 billion of investment in wind power project installations in 2015, for a cumulative investment total of more than $150 billion since the beginning of the 1980s.[4][5] With a record 484 MW of wind power capacity decommissioned in 2015, growth in cumulative "net" capacity in 2015 was 12%.



Source: AWEA project database

Figure 1. Annual and cumulative growth in U.S. wind power capacity

In 2015, growth was driven by recent improvements in the cost and performance of wind power technologies. State renewables portfolio standards (RPS) and corporate demand for wind power also played a role. Another key factor was the PTC, which, in December 2015, was extended for an additional 5 years—applying now to projects that begin construction before January 1, 2020, but with a progressive reduction in the value of the credit for projects starting construction after 2016. Substantial additional capacity additions are anticipated in the near term—in part due to the PTC extension.

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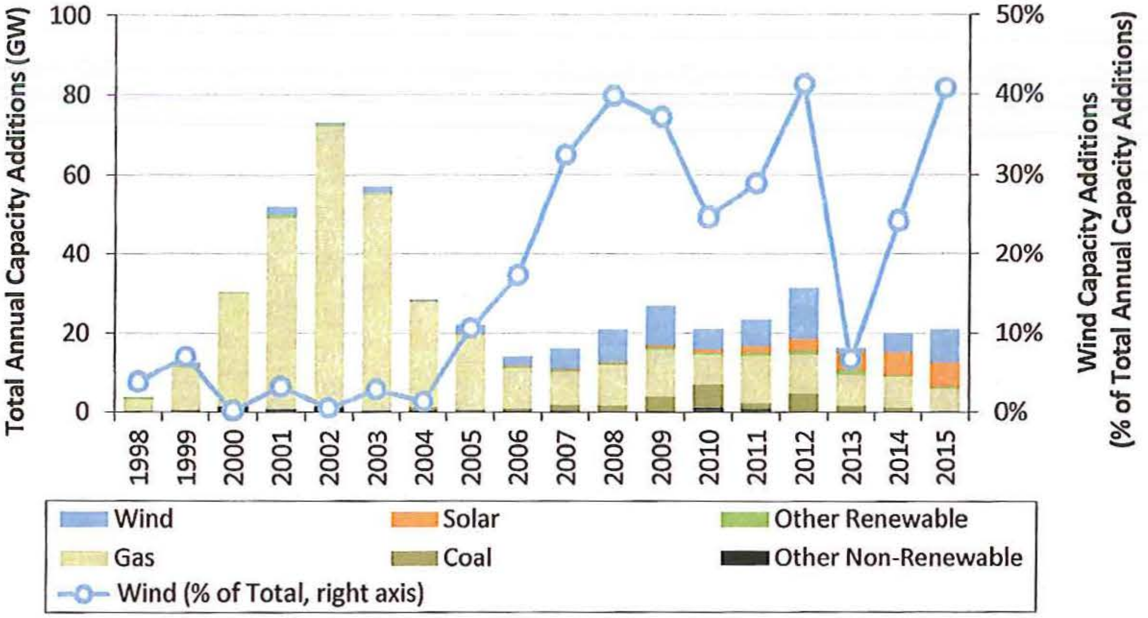
[3] When reporting annual wind power capacity additions, this report focuses on *gross* capacity additions of large wind turbines. The *net* increase in capacity each year can be somewhat lower, reflecting turbine decommissioning.

[4] All cost and price data are reported in real 2015$.

[5] These investment figures are based on an extrapolation of the average project-level capital costs reported later in this report and do not include investments in manufacturing facilities, research and development expenditures, or O&M costs.

Wind power represented the largest source of U.S. electric-generating capacity additions in 2015

Wind power has comprised a sizable share of generation capacity additions in recent years. In 2015, wind power constituted 41% of all U.S. generation capacity additions, up sharply from its 24% market share the year before and close to its all-time high (Figure 2).[6] For the second time, wind power was the largest source of annual new generating capacity, well ahead of the next two leading sources, solar power and natural gas.



Source: ABB, AWEA, GTM Research, Berkeley Lab

Figure 2. Relative contribution of generation types in annual capacity additions

Over the last decade, wind power represented 31% of total U.S. capacity additions, and an even larger fraction of new generation capacity in the Interior (54%) and Great Lakes (48%) regions (Figure 3; see Figure 29, later, for regional definitions). Its contribution to generation capacity growth over the last decade is somewhat smaller—but still significant—in the West (22%) and Northeast (21%), and considerably less in the Southeast (2%).

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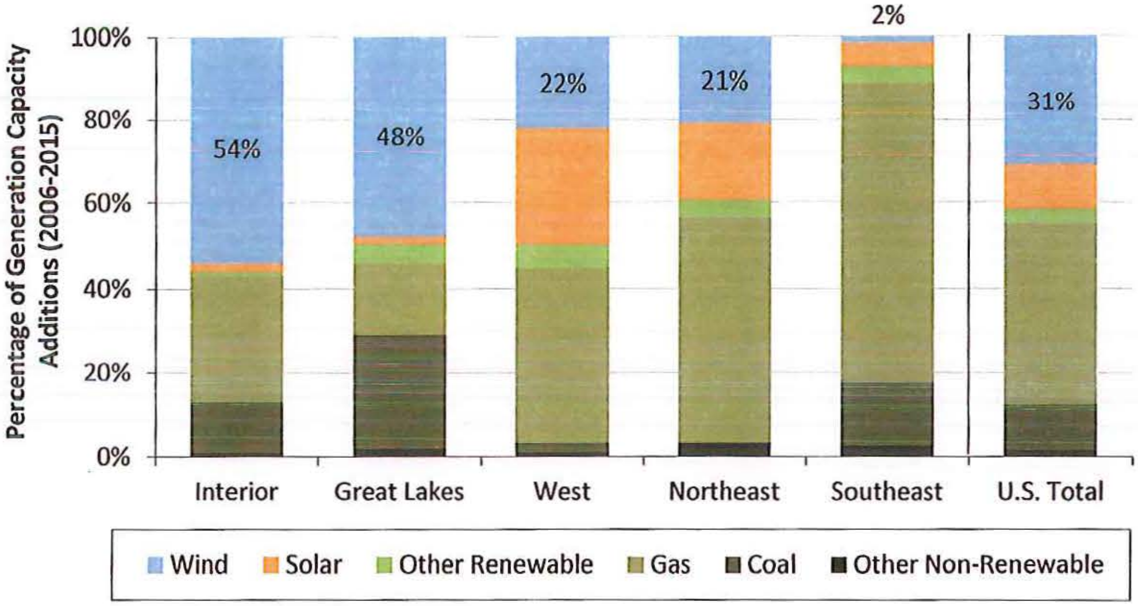
[6] Data presented here are based on gross capacity additions, not considering retirements. Furthermore, they include only the 50 U.S. states, not U.S. territories.



Source: ABB, AWEA, GTM Research, Berkeley Lab

Figure 3. Generation capacity additions by region (2006–2015)

The United States ranked second in annual wind additions in 2015, but was well behind the market leaders in wind energy penetration

Global wind additions yet again reached a new high in 2015, with roughly 63,000 MW of new capacity, 23% above the previous record of 51,000 MW added in 2014. Cumulative global capacity stood at approximately 434,000 MW at the end of the year (Navigant 2016a; Table 1).[7] The United States ended 2015 with 17% of total global wind power capacity, a distant second to China by this metric (Table 1).[8] On the basis of wind power production, however, the United States remained the leading country globally in 2015 (AWEA 2016a). Annual growth in cumulative capacity in 2015 was 23% for the United States and 17% globally.

After leading the world in annual wind power capacity additions from 2005 through 2008, and then losing the mantle to China from 2009 through 2011, the United States narrowly regained the global lead in 2012. In 2013, the United States dropped precipitously to 6th place in annual additions, but then regained ground, rising to 3rd place in 2014 and 2nd place in 2015 (Table 1). The U.S. wind power market represented 14% of global installed capacity in 2015.

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[7] Yearly and cumulative installed wind power capacity in the United States are from the present report, while global wind power capacity comes from Navigant (2016a) but are updated with the U.S. data presented here. Some disagreement exists among these data sources and others.

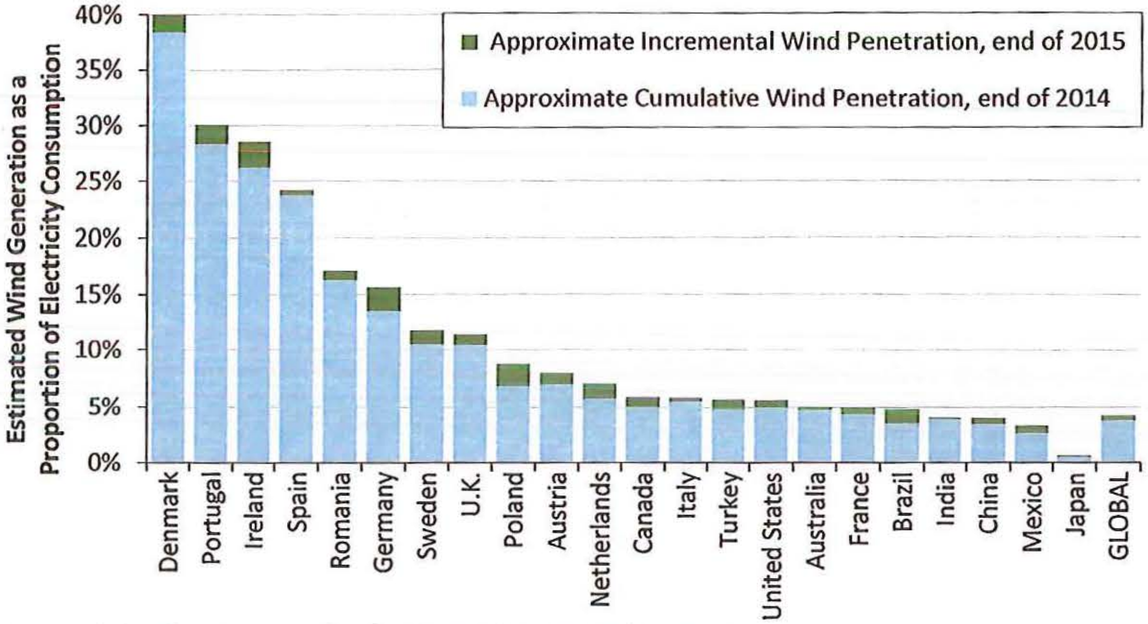
[8] Wind power additions and cumulative capacity in China include capacity that was installed but that had not yet begun to deliver electricity by the end of 2015, due to a lack of coordination between wind developers and transmission providers and the lengthier time that it takes to build transmission and interconnection facilities. All of the U.S. capacity reported here, on the other hand, was capable of electricity delivery.

Table 1. International Rankings of Wind Power Capacity

Annual Capacity (2015, MW)		Cumulative Capacity (end of 2015, MW)	
China	30,293	China	145,053
United States	8,598	United States	73,992
Germany	6,013	Germany	44,986
Brazil	2,754	India	25,352
India	2,623	Spain	22,665
Canada	1,506	United Kingdom	13,388
Poland	1,266	Canada	11,190
France	1,073	France	10,243
United Kingdom	975	Brazil	9,346
Turkey	956	Italy	8,851
Rest of World	7,078	*Rest of World*	68,464
TOTAL	63,135	TOTAL	433,530

Source: Navigant; AWEA project database for U.S. capacity

A number of countries have achieved relatively high levels of wind energy penetration in their electricity grids. Figure 4 presents data on end-of-2015 (and end-of-2014) installed wind power capacity, translated into projected annual electricity supply based on assumed country-specific capacity factors and then divided by projected 2016 (and 2015) electricity consumption. Using this approximation for the contribution of wind power to electricity consumption, and focusing only on those countries with the greatest cumulative installed wind power capacity, end-of-2015 installed wind power is estimated to supply the equivalent of roughly 40% of Denmark's electricity demand, and between 20% to 30% of Portugal, Ireland, and Spain's demand. In the United States, the cumulative wind power capacity installed at the end of 2015 is estimated, in an average year, to equate to 5.6% of the nation's electricity demand. On a global basis, wind energy's contribution is estimated to be approximately 4.3%.



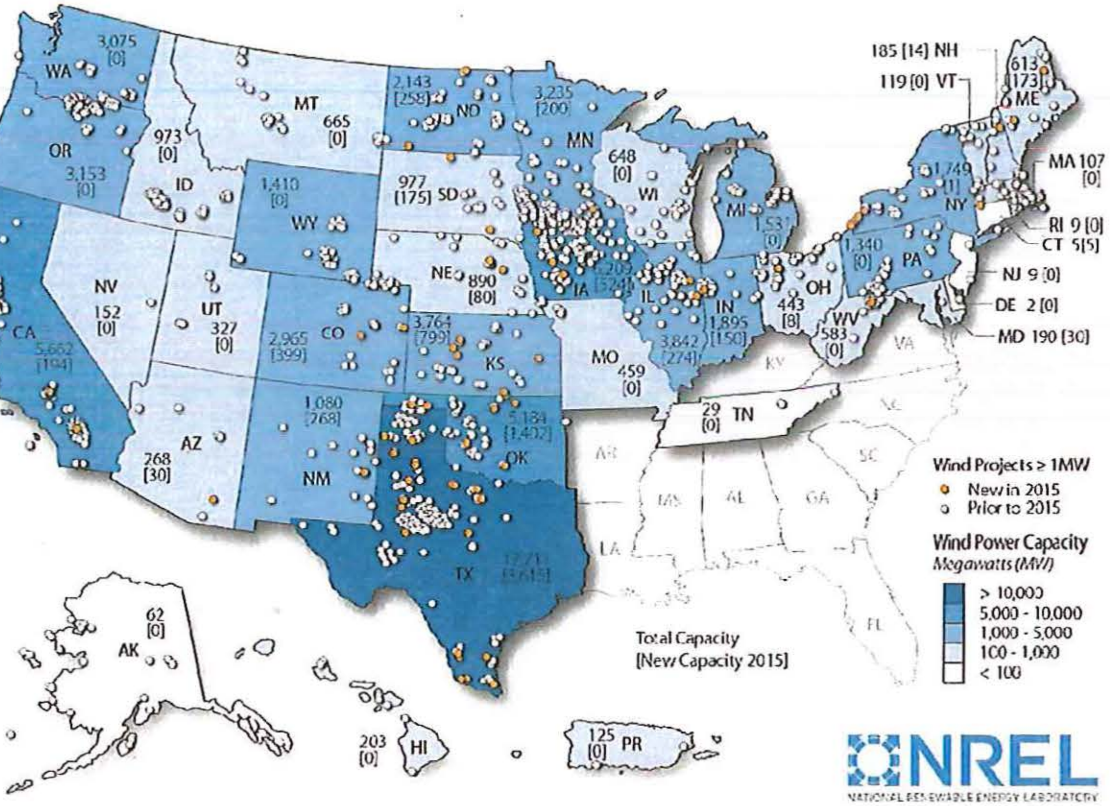
Source: Berkeley Lab estimates based on data from Navigant, EIA, and elsewhere

Figure 4. Approximate wind energy penetration in the countries with the greatest installed wind power capacity

Texas installed the most capacity in 2015 with 3,615 MW, while twelve states meet or exceed 10% wind energy penetration

New utility-scale wind turbines were installed in 20 states in 2015. Texas installed the most new wind capacity of any state, with 3,615 MW. As shown in Figure 5 and Table 2, other leading states in terms of new capacity included Oklahoma (1,402 MW), Kansas (799 MW), Iowa (524 MW), and Colorado (399 MW).

On a cumulative basis, Texas remained the clear leader among states, with 17,711 MW installed at the end of 2015—nearly three times as much as the next-highest state (Iowa, with 6,209 MW). In fact, Texas has more wind capacity than all but five countries—including the rest of the United States—worldwide. States distantly following Texas in cumulative installed capacity include Iowa, California, Oklahoma, Illinois, Kansas, Minnesota, Oregon, and Washington—all with more than 3,000 MW. Thirty-five states, plus Puerto Rico, had more than 100 MW of wind capacity as of the end of 2015, with 24 of these topping 500 MW, 17 topping 1,000 MW, and 11 topping 2,000 MW. Although all commercial wind projects in the United States to date have been installed on land, offshore development activities continued in 2015, as discussed in the next section.



Note: Numbers within states represent cumulative installed wind capacity and, in brackets, annual additions in 2015.

Figure 5. Location of wind power development in the United States

Some states have realized high levels of wind energy penetration. The right half of Table 2 lists the top 20 states based on actual wind electricity generation in 2015 divided by total in-state electricity generation in 2015.[9] Iowa leads the list, with 31.3% wind penetration, followed by South Dakota (25.5%) and Kansas (23.9%). A total of twelve states have achieved wind penetration levels of 10% or higher.

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[9] Wind energy penetration can either be expressed as a percentage of in-state load or in-state generation. In-state generation is used here, primarily because wind energy (like other energy resources) is often sold across state lines, which tends to distort penetration levels expressed as a percentage of in-state load. Also note that by focusing on generation in 2015, Table 2 does not fully capture the impact of new wind power capacity added during 2015 (particularly if added towards the end of the year).

Table 2. U.S. Wind Power Rankings: the Top 20 States

Installed Capacity (MW)				Percentage of In-State Generation	
Annual (2015)		Cumulative (end of 2015)		Actual (2015)*	
Texas	3,615	Texas	17,711	Iowa	31.3%
Oklahoma	1,402	Iowa	6,209	South Dakota	25.5%
Kansas	799	California	5,662	Kansas	23.9%
Iowa	524	Oklahoma	5,184	Oklahoma	18.4%
Colorado	399	Illinois	3,842	North Dakota	17.7%
Illinois	274	Kansas	3,764	Minnesota	17.0%
New Mexico	268	Minnesota	3,235	Idaho	16.2%
North Dakota	258	Oregon	3,153	Vermont	15.4%
Minnesota	200	Washington	3,075	Colorado	14.2%
California	194	Colorado	2,965	Oregon	11.3%
South Dakota	175	North Dakota	2,143	Maine	10.5%
Maine	173	Indiana	1,895	Texas	10.0%
Indiana	150	New York	1,749	Nebraska	8.0%
Nebraska	80	Michigan	1,531	Wyoming	7.7%
Arizona	30	Wyoming	1,410	Montana	6.6%
Maryland	30	Pennsylvania	1,340	Washington	6.5%
New Hampshire	14	New Mexico	1,080	New Mexico	6.3%
Ohio	8	South Dakota	977	California	6.2%
Connecticut	5	Idaho	973	Hawaii	6.1%
New York	1	Nebraska	890	Illinois	5.5%
Rest of U.S.	0	*Rest of U.S.*	5,203	*Rest of U.S.*	1.0%
TOTAL	8,598	TOTAL	73,992	TOTAL	4.7%

* Based on 2015 wind and total generation by state from EIA's *Electric Power Monthly.*
Source: AWEA project database, EIA

The first commercial offshore turbines are expected to be commissioned in the United States in 2016 amid mixed market signals

At the end of 2015, global cumulative offshore wind power capacity stood at roughly 12,000 MW (Navigant 2016a), with Europe continuing as the primary center of activity. Navigant (2016a) reports more than 3,500 MW of new offshore wind capacity being commissioned in 2015, with more than 3,000 MW under construction at the end of 2015.[10]

The 30 MW Block Island project, developed by Deepwater Wind, began construction in 2015. All five jacket foundations were installed in 2015 and cable installation was expected to be complete by June 2016. Once installed, the project will consist of five GE Haliade 6 MW offshore wind turbines. The project is expected to be commissioned by the end of 2016, becoming the first commercial offshore wind power plant to operate in the United States.

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[10] Various data sources report different figures, in part due to differing perspectives on when to consider a project "completed."

A number of other high-profile projects have run into legal and political headwinds:

- National Grid and NSTAR canceled their power purchase agreements (PPA) with the 468 MW **Cape Wind** project after it failed to meet contractual deadlines. The Bureau of Ocean Energy Management (BOEM) approved the project's application to suspend the 28-year operations term of its offshore area lease, but denied the project's request to stop its annual lease payments (Hopper 2015). The Massachusetts Energy Facilities Siting Board denied Cape Wind's request for permit extension for its electricity transmission lines in April 2016.
- New Jersey passed the Offshore Wind Economic Development Act in 2010, creating a program for offshore renewable energy credits. However, as of the end of 2015, the New Jersey Board of Public Utilities (BPU) had twice rejected the 25 MW **Fishermen's Energy Atlantic City Windfarm's** application for the state's Offshore Renewable Energy Credit program. The State Supreme Court subsequently upheld the decision of the BPU. Fishermen's Energy continues to face roadblocks; legislative efforts to allow the project to reapply for BPU approval were vetoed by the governor. In 2012, DOE selected Fishermen's Energy as one of seven demonstration projects to receive $4 million in funding, and chose it as one of three projects eligible for an additional $46.7 million in funding in 2014. That eligibility was renewed in 2016 upon evaluation of the project against established milestones.
- Dominion Virginia Power announced that it would delay the 12 MW **Virginia Offshore Wind Technology Advancement Project** (VOWTAP) after initial bids for construction came in at 63%-74% above initial estimates. A second round of bidding reduced the cost of the project to 30%-65% above the initial estimate.[11] BOEM approved a research lease for the project in March 2016. DOE chose VOWTAP as one of seven offshore projects (including Fishermen's Energy) to receive $4 million in 2012 and, in 2014, up to an additional $46.7 million in funding. However, DOE withdrew the offer in May 2016 upon evaluation of the project, determining that VOWTAP could not guarantee commissioning prior to 2020.

The high cost of offshore wind coupled with the complex regulatory environment serve as key challenges for the U.S. offshore wind industry. The mechanisms for planning, siting, and permitting offshore wind projects are fragmented, requiring developers to engage with multiple local, state, and federal agencies and stakeholders. Furthermore, regulatory processes to secure site control and construction authorization are mostly decoupled from offtake agreements that support the economics of an offshore wind project. U.S. developers with competitive lease auctions must separately negotiate PPAs, which increases uncertainty relative to European markets. Meanwhile, due to the lack of sufficient policy support to cover the high cost of offshore wind in most states, offtake agreements and financing have been hard to obtain. NREL estimates that the levelized cost of fixed-bottom offshore wind energy in 2014 was $193/MWh in the United States (Moné et al. 2015).

Despite these challenges, the United States remains interested in offshore wind project development. Key drivers include the close proximity of offshore wind resources to population centers, which could address transmission congestion, the potential for local economic development benefits, and superior capacity factors and larger potential project sizes compared to limited developable land-based wind resources in some coastal regions.

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[11] The initial projection for VOWTAP was $230 million, the first round of bidding came in at $375-400 million, and the second round of bidding came in at $300-380 million.

Policy support for offshore wind originates in state initiatives and policies as well as federal incentives and programs. Of those states with RPS requirements, Maryland, New Jersey, and Maine have offshore-specific carve-out mandates or goals. At the federal level, the recent extension of the PTC and ITC may help support offshore projects that are able to meet the relevant deadlines. In addition, federal support in the form of regulatory approvals and technology investment is boosting commercial interest. BOEM had granted five leases for sites in Rhode Island, Massachusetts, Maryland, and Virginia as of the end of 2015. In 2015, BOEM issued four additional leases from competitive auctions for offshore wind areas in Massachusetts and New Jersey. In January 2015, the Massachusetts auction received bids for two of the four available zones, potentially adding up to 1.4 GW of offshore development.[12] In November 2015, the New Jersey auction resulted in two lease areas totaling more than 3 GW of announced potential offshore wind power.[13] Further competitive leases are planned in New York, North Carolina, and South Carolina.

DOE has also made significant investments in offshore wind energy, including funding for advanced technology demonstration partnerships. In 2012, DOE launched the Offshore Wind Advanced Technology Demonstration program by selecting seven offshore demonstration projects to receive up to $4 million to complete engineering, design, and permitting phases of development. In 2014, DOE selected three innovative projects from the seven demonstration projects for additional federal funding of $6.7 million each to finalize the initial development phase. These three projects, Dominion Power's VOWTAP (12 MW, Virginia), Principle Power's WindFloat Pacific (up to 30 MW, Oregon), and Fishermen's Energy Atlantic City Windfarm (at least 24 MW, New Jersey), also received eligibility to receive up to $40 million in funding for future phases. In addition, DOE selected two alternate projects, University of Maine's 12 MW Aqua Ventus project in Maine and Lake Erie Energy Development Corporation's 18 MW Icebreaker Project in Ohio, to receive $3 million each to complete the engineering designs of their technology concepts.

In May 2016, DOE decided that Principle Power's WindFloat Pacific project in Oregon and Dominion's VOWTAP in Virginia would no longer be eligible for the funding due to their inability to guarantee project milestones. Instead, DOE selected the two alternate projects in Maine and Ohio to receive the additional funding as part of the demonstration program.

Figure 6 identifies 23 proposed offshore wind projects in the United States in various stages of development. These projects total more than 16 GW of potential capacity, of which approximately 10 GW have obtained site control through leases or determinations of no competitive interest.[14] The proposed projects are primarily located in the Northeast and Mid-Atlantic, with one project each in the Great Lakes, Pacific Northwest, and California. Developers have also filed lease requests to BOEM for three areas in Hawaii in 2015 and 2016.

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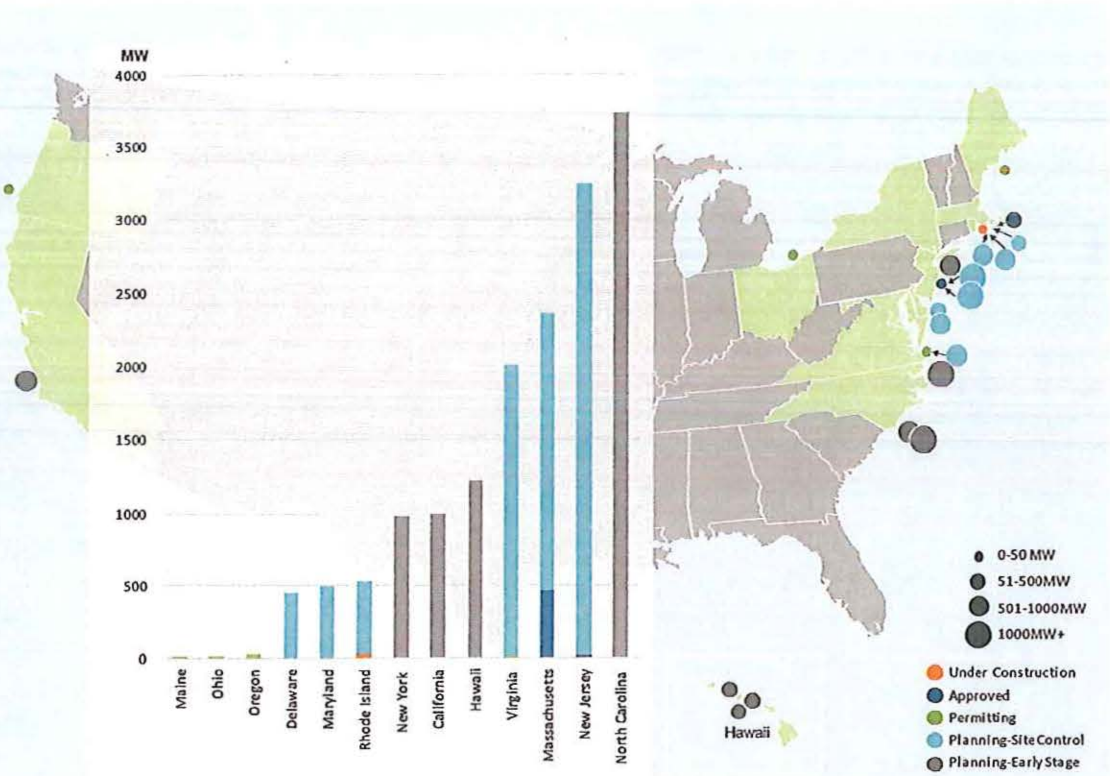
[12] The potential capacity for the two lease areas is based on announced estimated capacity by the developers, Offshore MW LLC (400 MW) and DONG Energy (1000 MW).

[13] The potential capacity of 3 GW is based on the announced capacity by DONG Energy (1000 MW) and estimates by NREL for US Wind's lease area (2230 MW).

[14] A project reaches the site control phase when the developer obtains exclusive development rights to a site.



Note: Capacities of projects are based on owner/developer announced capacity. In cases where announced capacity is unavailable, the capacity refers to the estimated maximum potential, which assumes an average capacity density of 3 MW/ km^2 based on spacing of 9 to 10 rotor diameters developed. For methodology of estimated maximum potential, please refer to Musial et al. (2013a, 2013b). For definitions of the different stages of development, please refer to Smith et al. (2015).

Figure 6. Offshore wind power projects under development in the United States as of June 2016

Of the projects identified in Figure 6, Deepwater Wind's Block Island project off the coast of Rhode Island is the only one that has a PPA. Achievement of this milestone enabled the project to close financing and to begin construction in spring 2015. Other projects are working with regulators to finalize design, secure permits, and/or establish power sales agreements. The recent challenges highlighted above suggest that the schedules for these projects are subject to uncertainty.

Data from interconnection queues demonstrate that a substantial amount of wind power capacity is under consideration

One testament to the continued interest in land-based wind energy is the amount of wind power capacity currently working its way through the major transmission interconnection queues across the country. Figure 7 provides this information for wind power and other resources aggregated across 34 different interconnection queues administered by independent system operators (ISOs), regional transmission organizations (RTOs), and utilities.[15] These data should be interpreted with

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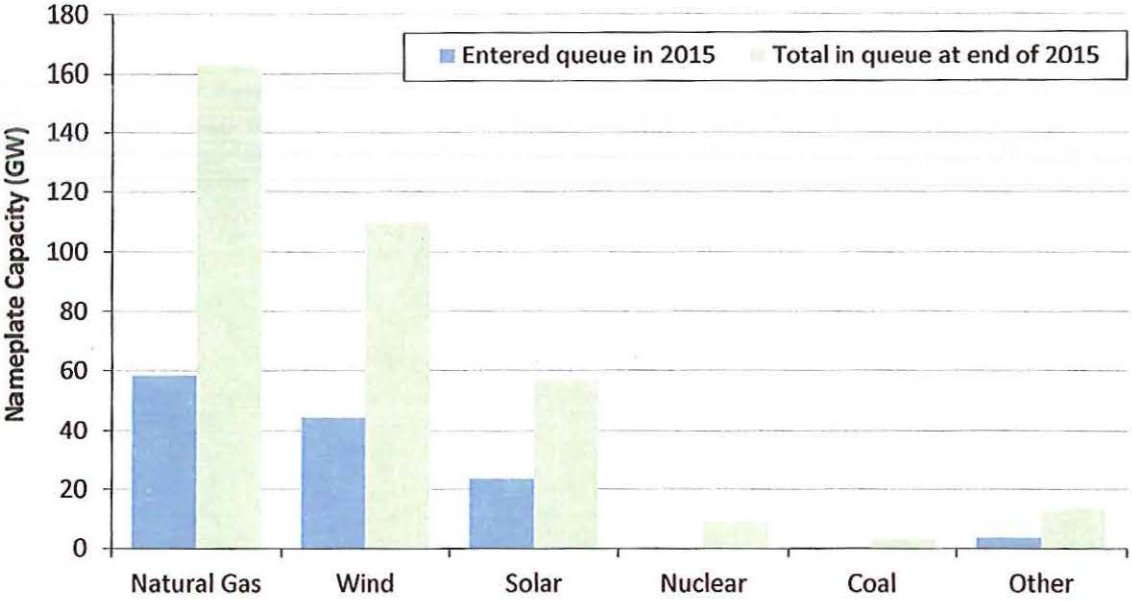
[15] The queues surveyed include PJM Interconnection (PJM), Midcontinent Independent System Operator (MISO), New York ISO (NYISO), ISO-New England (ISO-NE), California ISO (CAISO), Electric Reliability Council of Texas (ERCOT), Southwest Power Pool (SPP), Western Area Power Administration (WAPA), Bonneville Power

caution: placing a project in the interconnection queue is a necessary step in project development, but being in the queue does not guarantee that a project will be built. Efforts have been made by FERC, ISOs, RTOs, and utilities to reduce the number of speculative projects that have clogged these queues in past years. One consequence of those efforts is that the total amount of wind power capacity in the nation's interconnection queues has declined dramatically since 2009.



Source: Exeter Associates review of interconnection queues

Figure 7. Generation capacity in 34 selected interconnection queues, by resource type

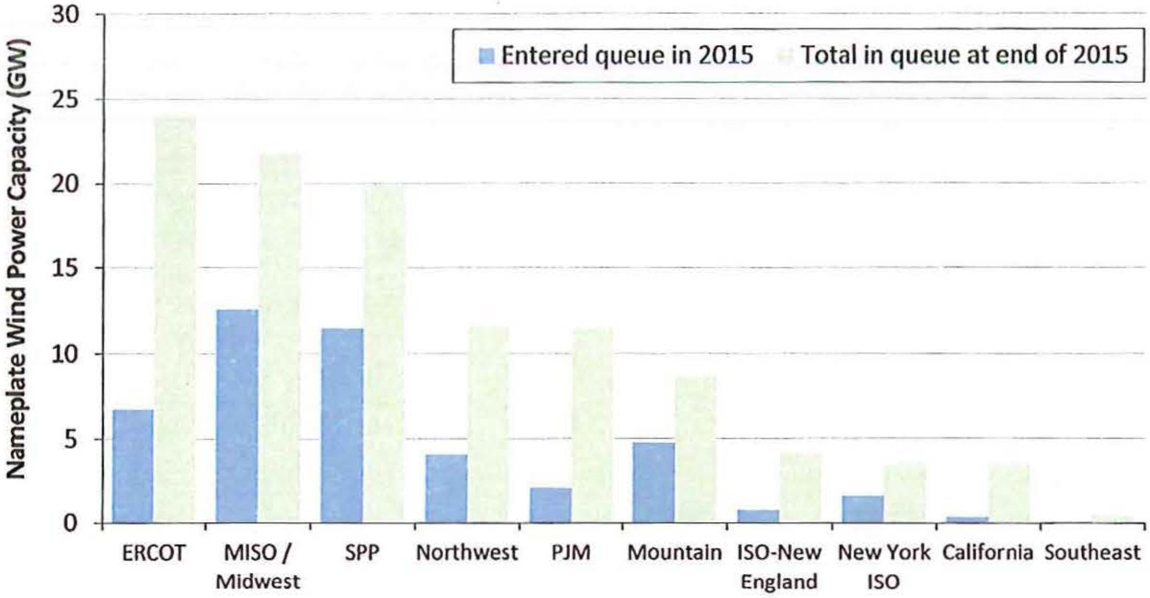
Even with this important caveat, the amount of wind capacity in the nation's interconnection queues still provides at least some indication of the amount of planned development. At the end of 2015, there were 110 GW of wind power capacity within the interconnection queues reviewed for this report—almost one-and-a-half times the installed wind power capacity in the United States. This 110 GW is an increase from the end of 2014 (96 GW), and represented 31% of all generating capacity within these selected queues at that time, higher than all other generating sources except for natural gas. In 2015, 45 GW of wind power capacity entered the interconnection queues, compared to 58 GW of natural gas and 24 GW of solar. The 45 GW of new wind capacity entering the queues in 2015 is the largest annual sum since 2010.

Of note, however, is that the total amount of wind, coal, and nuclear power in the sampled interconnection queues (considering gross additions and project drop-outs) has generally declined in recent years, whereas natural gas and solar capacity has increased or held steady.

Administration (BPA), Tennessee Valley Authority (TVA), and 24 other individual utilities. To provide a sense of sample size and coverage, the ISOs, RTOs, and utilities whose queues are included here have an aggregated non-coincident (balancing authority) peak demand of about 88% of the U.S. total. Figures 7 and 8 only include projects that were active in the queue at the end of 2015 but that had not yet been built; suspended projects are not included.

Since 2009, for example, the amount of wind power capacity has dropped by 64%, coal by 89%, and nuclear by 67%, whereas solar capacity has increased by 68% and natural gas by 47%.

The wind capacity in the interconnection queues is spread across the United States, as shown in Figure 8, with larger amounts in ERCOT (22%), the Midwest (20%), Southwest Power Pool (SPP) (18%), the Northwest (11%), and the PJM Interconnection (11%). Somewhat smaller amounts are found in the Mountain region (8%), ISO-New England (4%), New York ISO (3%), California (3%), and the Southeast (0.5%).



Source: Exeter Associates review of interconnection queues

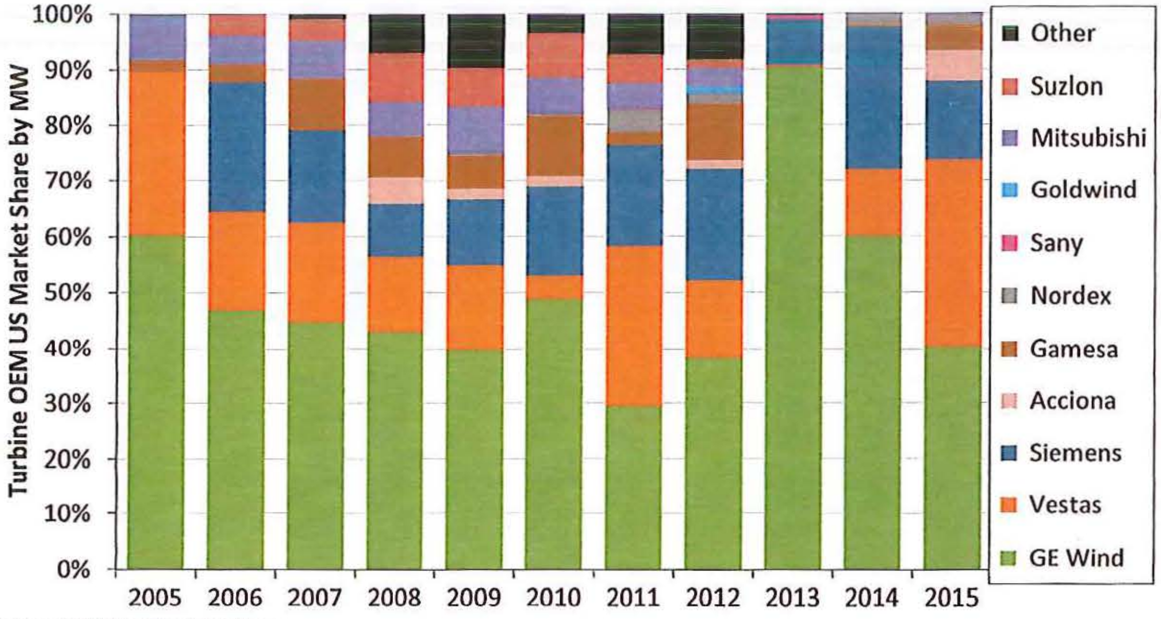
Figure 8. Wind power capacity in 34 selected interconnection queues, by region

As a measure of the near-term development pipeline, ABB (2016) estimates that—as of June 2016—approximately 29 GW of wind power capacity could be characterized in one of three ways: (a) under construction or in site preparation (8 GW); (b) in development and permitted (11 GW); or (c) in development with a pending permit and/or regulatory applications (9 GW). These totals are similar to last year at approximately the same time (June 2015), indicating that the development pipeline remains strong. AWEA (2016b), meanwhile, reports that more than 15 GW of wind power capacity was under construction or at an advanced stage of development at the end of the first quarter of 2016. Supporting these figures, EIA (2016c) reports over 15 GW of planned wind power additions for 2016 and 2017.

3. Industry Trends

GE and Vestas captured 73% of the U.S. wind power market in 2015

Of the 8,598 MW of wind installed in 2015, 40% (3,468 MW) deployed turbines from GE Wind, with Vestas coming in second (2,870 MW, 33% market share), followed by Siemens (1,219 MW, 14%) (Figure 9 and Table 3).[16] Other suppliers included Acciona (465 MW), Gamesa (402 MW), Nordex (138 MW), Sany (20 MW), and Goldwind (8 MW). Some recent OEM consolidation has also occurred, with Nordex merging with Acciona, GE acquiring Alstom, and more recently in mid-2016, Siemens merging with Gamesa.



Source: AWEA project database

Figure 9. Annual U.S. market share of wind turbine manufacturers by MW, 2005–2015

According to Navigant (2016a), Goldwind and Vestas were the top two suppliers of turbines worldwide in 2015, followed by GE, Siemens, and Gamesa. On a worldwide basis, Chinese turbine manufacturers continued to occupy positions of prominence, with five of the top 10 spots in the ranking; to date, however, the growth of Chinese turbine manufacturers has been based almost entirely on sales to the Chinese market (though both Goldwind and Sany turbines were installed in the U.S. in 2015, with a limited number of Chinese turbines also installed in earlier years). Other than GE, no other U.S.-owned utility-scale turbine manufacturer plays a meaningful role in global or U.S. large-wind-turbine supply.

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[16] Market share is reported in MW terms and is based on project installations in the year in question.

Table 3. Annual U.S. Turbine Installation Capacity by Manufacturer

Manufacturer	Turbine Installations (MW)										
	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
GE Wind	1,431	1,146	2,342	3,585	3,995	2,543	2,006	5,016	984	2,912	3,468
Vestas	699	439	948	1,120	1,489	221	1,969	1,818	4	584	2,870
Siemens	0	573	863	791	1,162	828	1,233	2,638	87	1,241	1,219
Acciona	0	0	0	410	204	99	0	195	0	0	465
Gamesa	50	74	494	616	600	566	154	1,341	0	23	402
Nordex	0	0	3	0	63	20	288	275	0	90	138
Sany	0	0	0	0	0	0	10	2	8	0	20
Goldwind	0	0	0	0	5	0	5	155	0	0	8
Mitsubishi	190	128	356	516	814	350	320	420	0	0	0
Suzlon	0	92	198	738	702	413	334	187	0	0	0
Other	4	2	50	587	973	180	502	1,086	4	2	2
TOTAL	2,374	2,457	5,253	8,362	10,005	5,216	6,820	13,131	1,087	4,854	8,598

Source: AWEA project database

The manufacturing supply chain continued to adjust to swings in domestic demand for wind equipment

As the cumulative capacity of U.S. wind projects has grown over the last decade, foreign and domestic turbine equipment manufacturers have localized and expanded operations in the United States. Yet, the wind industry's domestic supply chain continues to deal with conflicting pressures: an upswing in near- to medium-term expected growth, but also strong international competitive pressures and possible reduced demand over time as the PTC is phased down. As a result, though many manufacturers increased the size of their U.S. workforce in 2015, market expectations for significant supply-chain expansion have become more pessimistic.

Figure 10 presents a non-exhaustive list of the more than 145 wind turbine and component manufacturing and assembly facilities operating in the United States at the end of 2015, focusing on the utility-scale wind market.[17] Figure 11 segments those facilities by major component.

Only one new wind-related manufacturing facility opened in 2015: MM Composite, a composite parts manufacturer that had previously operated solely within the Siemens Fort Madison, Iowa blade facility. Located in Mount Pleasant, Iowa, the new facility will allow MM Composites to increase its overall workforce. Also announced in 2015 was a planned 2016 opening of a tower manufacturing facility in Amarillo, Texas by GRI Renewables. That facility is expected to employ up to 300 workers and manufacture up to 400 towers annually when it reaches full

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[17] The data on existing, new, and announced manufacturing facilities presented here differ from those presented in AWEA (2016a) due, in part, to methodological differences. For example, AWEA includes data on a large number of smaller component suppliers that are not included in this report; the figure presented here also does not include research and development and logistics centers, or materials suppliers. As a result, AWEA (2016a) reports a much larger number of wind-related manufacturing facilities, over 500 in total.

production. At the same time, at least three existing wind turbine or component manufacturing facilities were consolidated, closed, or stopped serving the industry in 2015.

Notwithstanding the recent supply chain consolidation and slow additions of new facilities, there remain a large number of domestic manufacturing facilities. Additionally, several manufacturers either expanded their workforce in 2015 to meet demand (e.g., Vestas, LM Windpower, MFG Aberdeen), remodeled facilities to meet industry standards (e.g., LM Windpower,), or began expansions of existing facilities (e.g., Vestas, MFG Aberdeen). As also shown in Figure 10, turbine and component manufacturing facilities are spread across the country. Many manufacturers have chosen to locate in markets with substantial wind power capacity or near already established large-scale original equipment manufacturers (OEMs). However, even states that are relatively far from major wind power markets have manufacturing facilities. Most states in the Southeast, for example, have wind manufacturing facilities despite the fact that there are few wind power projects in that region. Workforce considerations, transportation costs, and state and local incentives are among the factors that typically drive location decisions.

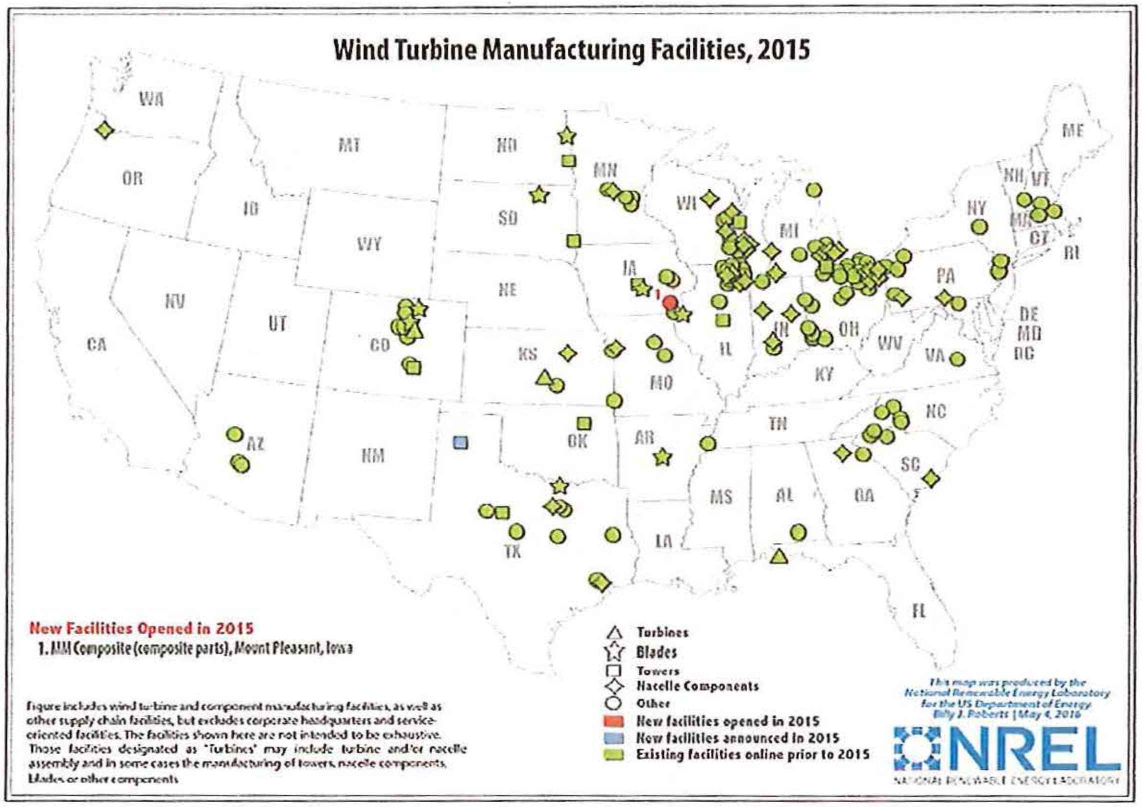
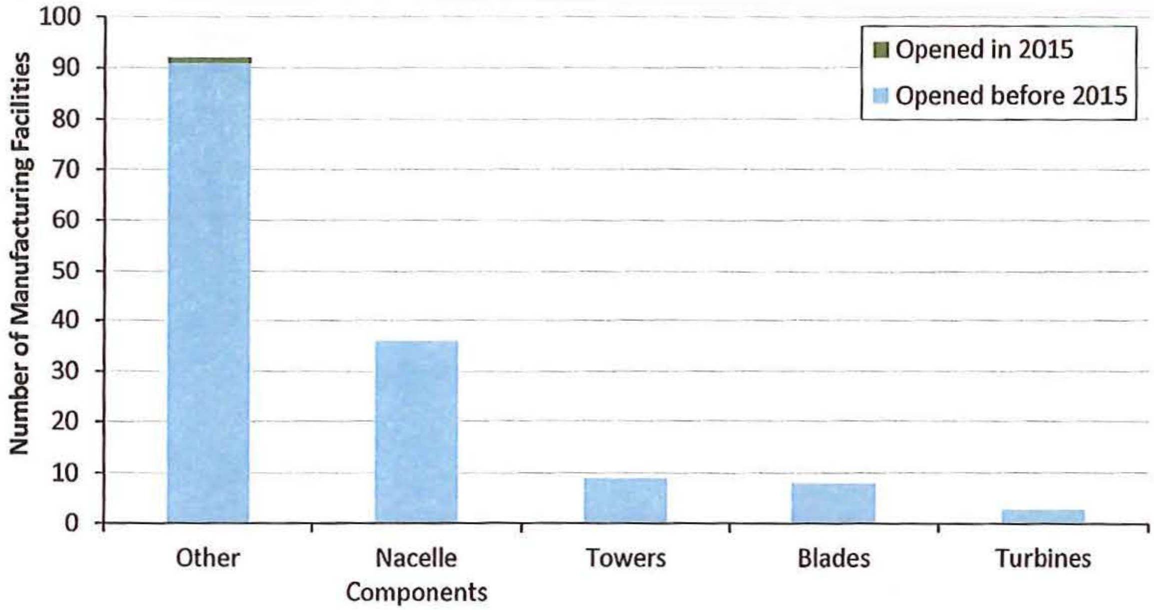


Figure 10. Location of existing and new turbine and component manufacturing facilities

Among the many other facets of the domestic supply chain, in 2010, 9 of the 11 wind turbine OEMs with the largest shares of the U.S. market owned at least one domestic manufacturing facility (Acciona, Clipper, DeWind, Gamesa, GE, Nordex, Siemens, Suzlon, and Vestas).[18] Since that time, a number of these facilities have been closed, in part reflecting the increased concentration of the U.S. wind industry among the three top OEMs, demand uncertainty, and a desire to consolidate production at centralized facilities overseas in order to gain economies of scale. For example, though no final decision has been announced regarding Alstom's Amarillo, Texas facility, the plant was idled when the GE/Alstom merger was announced. Similarly, the Nordex/Acciona merger has left the future of the Acciona West Branch, Iowa facility in question. The plant is currently idled. Nonetheless, the three major OEMs active in the U.S. market (GE, Vestas, Siemens) still had one or more operating manufacturing facilities in the United States at the end of 2015. In contrast, a decade earlier (2004), there was only one active utility-scale wind energy OEM assembling nacelles in the United States (GE).



Note: Manufacturing facilities that produce multiple components are included in multiple bars. "Other" includes facilities that produce items such as: enclosures, power converters, slip-rings, inverters, electrical components, tower internals, climbing devices, couplings, castings, rotor hubs, plates, walkways, doors, bearing cages, fasteners, bolts, magnetics, safety rings, struts, clamps, transmission housings, embed rings, electrical cable systems, yaw/pitch control systems, bases, generator plates, slew bearings, flanges, anemometers, and template rings.

Source: National Renewable Energy Laboratory

Figure 11. Number of operating wind turbine and component manufacturing facilities in the U.S.

In aggregate, domestic turbine nacelle assembly capability—defined here as the "maximum" nacelle assembly capability of U.S. plants if all were operating at maximum utilization—grew from less than 1.5 GW in 2006 to more than 13 GW in 2012, before dropping to roughly 10 GW in 2015 (Figure 12; Bloomberg NEF 2015a, AWEA 2016a). In addition, AWEA (2016a) reports that U.S. manufacturing facilities have the capability to produce 10,500 individual blades (~7 GW) and more than 3,100 towers (~6.2 GW) annually. Figure 12 contrasts this

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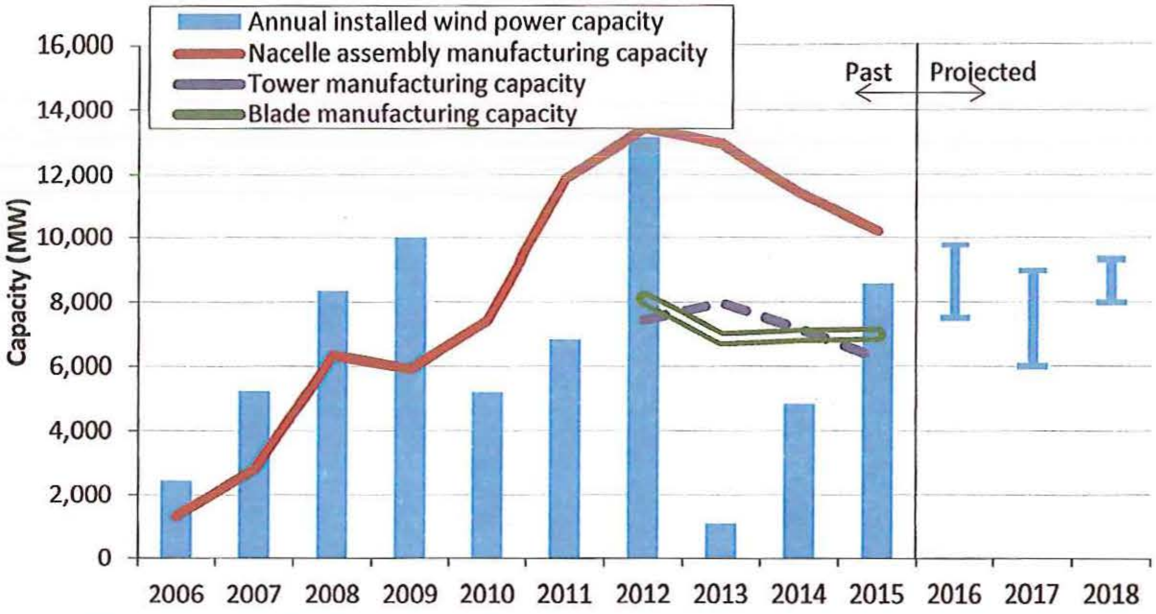
[18] Nacelle assembly is defined here as the process of combining the multitude of components included in a turbine nacelle to produce a complete turbine nacelle unit.

equipment manufacturing capability with past U.S. wind additions as well as near-term forecasts of future U.S. installations (see Chapter 9, "Future Outlook"). It demonstrates that domestic manufacturing capability for blades, towers, and nacelle assembly is reasonably well balanced against anticipated near-term market demand. Such comparisons should be made with care, however, because maximum factory utilization is uncommon, and because turbine imports into and exports from the United States also impact the balance of supply and demand.



Source: AWEA, Bloomberg NEF, EIA, IHS, Navigant, MAKE, UBS, Berkeley Lab

Figure 12. Domestic wind manufacturing capability vs. U.S. wind power installations

Fierce competition throughout the supply chain has caused many manufacturers to execute cost-cutting measures globally and domestically in recent years. As a result of these cost savings, coupled with booming demand, the profitability of turbine OEMs has generally rebounded over the last three years, after a number of years in decline (Figure 13).[19] Moreover, with recent and near-term expected continued strong growth in U.S. wind installations, wind-related job totals in the U.S. reached a new all-time high in 2015. AWEA (2016a) estimates that the wind industry employed 88,000 full-time[20] workers in the United States at the end of 2015—an increase of more than 15,000 from the end of 2014. The 88,000 jobs include, among others, those in the manufacturing and supply chain (~21,000); construction, development, and transportation (~38,000); and plant operations (~19,000). Consistent with the growth in wind power construction activity, the largest increase from 2014 to 2015 was seen in the construction, development, and transportation category.

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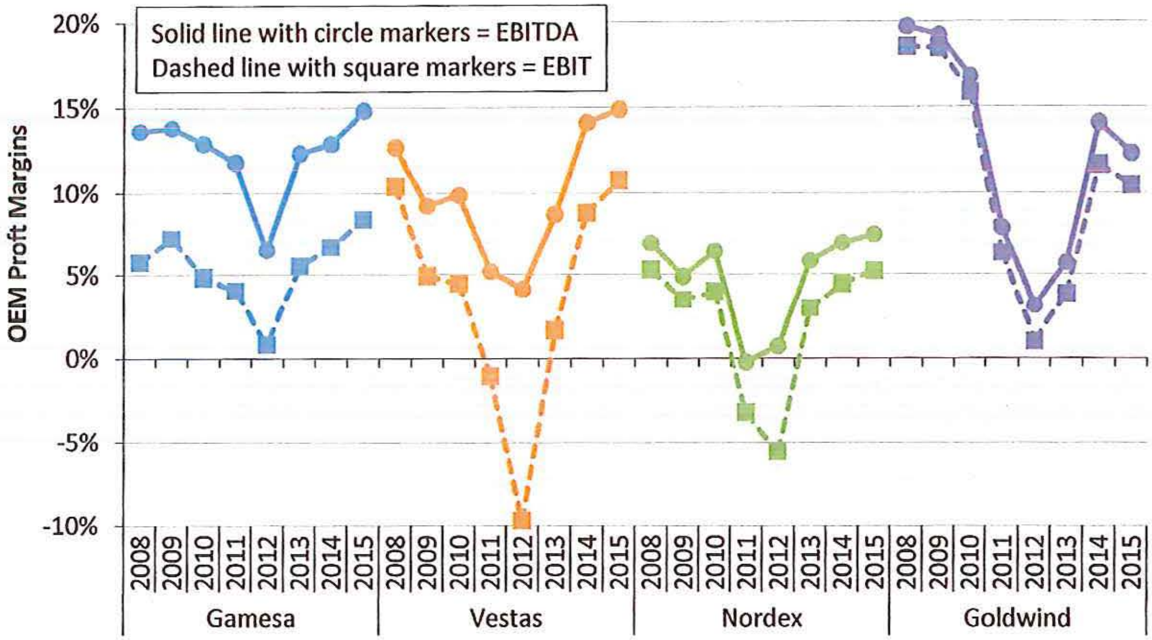
[19] Figure 13 only reports data for those OEMs that are "pure-play" wind turbine manufacturers. GE and Siemens—among the largest turbine suppliers in the U.S. market (along with Vestas)—are not included because they are multi-national conglomerates that do not report segmented financial data for their wind turbine divisions. Figure 13 depicts both EBIT (i.e., "earnings before interest and taxes," also referred to as "operating profit") and EBITDA (i.e., "earnings before interest, taxes, depreciation, and amortization") margins.

[20] Jobs are reported as full-time equivalents. For example, two people working full-time for 6 months are equal to one full-time job in that year.



Note: EBITDA = earnings before interest, taxes, depreciation and amortization

Source: OEM annual reports and financial statements

Figure 13. Turbine OEM global profitability over time

Domestic manufacturing content is strong for some wind turbine components, but the U.S. wind industry remains reliant on imports

The U.S. wind sector is reliant on imports of wind equipment, though the level of dependence varies by component: some components have a relatively high domestic share, whereas other components remain largely imported. These trends are revealed, in part, by data on wind power equipment trade from the U.S. Department of Commerce.[21]

Figure 14 presents data on the dollar value of estimated imports to the United States of wind-related equipment that can be tracked through trade codes. Specifically, the figure shows imports of wind-powered generating sets and nacelles (i.e., nacelles with blades, nacelles without blades, and, when imported as part of the same transaction, other turbine components) as well as imports of select turbine components that are shipped separately from the generating sets and nacelles.[22] The selected wind turbine components included in the figure consist only of those that can be tracked through trade codes: towers, generators (and generator parts), and blades and hubs.

Import estimates should be viewed with particular caution because the underlying data used to produce the Figure 14 are based on trade categories that are not all exclusive to wind energy (e.g., they could include generators for non-wind applications). Some of the import estimates

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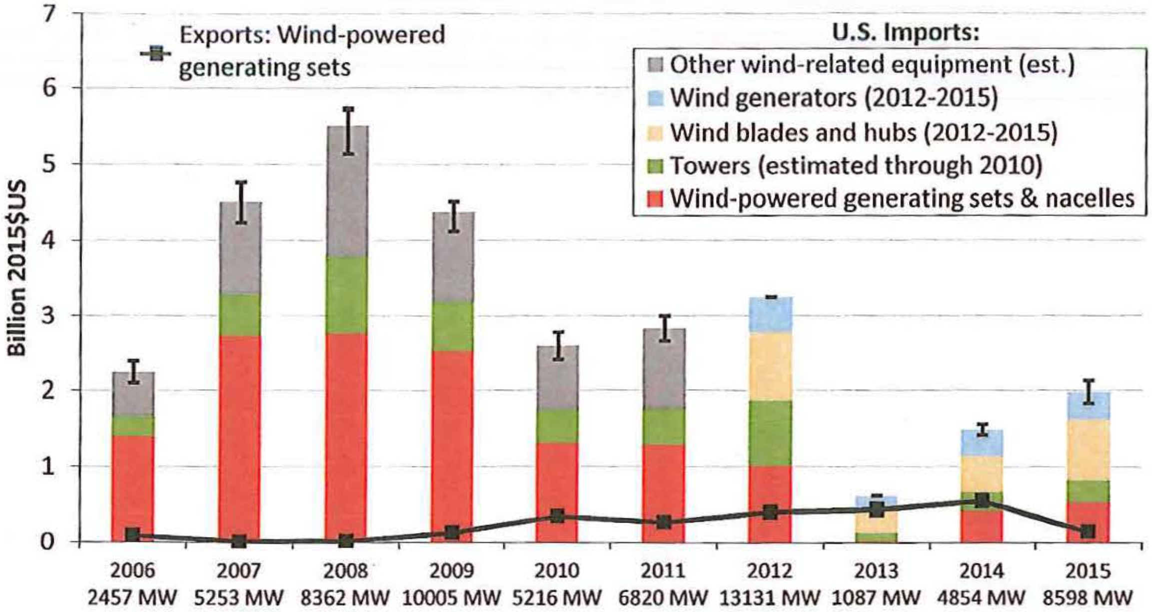
[21] See the appendix for further details on data sources and methods used in this section, including the specific trade codes considered.

[22] Wind turbine components such as blades, towers, and generators are included in the data on wind-powered generating sets and nacelles if shipped in the same transaction. Otherwise, these component imports are reported separately.

shown in Figure 14 therefore required assumptions about the fraction of larger trade categories likely to be represented by wind turbine components. The error bars in Figure 14 account for uncertainty in these assumed fractions. In 2012 and 2013, all trade categories shown were either specific to or largely restricted to wind power, and so no error bars are shown. After 2013, only nacelles (when shipped alone) are included in a trade category that is not largely exclusive to wind, and so the error bars shown for 2014 and 2015 only reflect the uncertainty in nacelle imports. More generally, as noted earlier, Figure 14 excludes comprehensive data on the import of wind equipment, as not all such equipment is clearly identified in trade categories. The impact of this omission on import and domestic content is discussed later.



Source: Berkeley Lab analysis of data from USITC DataWeb: http://dataweb.usitc.gov

Figure 14. Estimated imports of wind-powered generating sets, towers, generators, and blades and hubs, as well as exports of wind-powered generating sets and towers and lattice masts

As shown, the estimated imports of tracked wind-related equipment into the United States substantially increased from 2006–2008, before falling through 2010, increasing somewhat in 2011 and 2012, and then dropping sharply in 2013 with the simultaneous drop in U.S. wind installations. In 2014 and 2015, as U.S. wind installations bounced back, so did imports of wind-related turbine equipment. These overall trends are driven by a combination of factors: changes in the share of domestically manufactured wind turbines and components (versus imports), changes in the annual rate of wind power capacity installations, and changes in wind turbine prices. Because imports of wind turbine component parts occur in additional, broad trade categories different from those included in Figure 14, the data presented here understate the aggregate amount of wind equipment imports into the United States.

Figure 14 also shows that exports of wind-powered generating sets from the United States have generally increased over time, rising from just $16 million in 2007 to $544 million in 2014. The year 2015 was a notable exception to this trend, however, with exports falling to $149 million. The largest destination markets for these exports over the entire 2006–2015 timeframe were

Canada (60%) and Brazil (27%); 2015 exports were also dominated by Canada (52%) and Brazil (19%). U.S. exports of 'towers and lattice masts' in 2015 totaled an additional $63 million (down from a peak of $170 million in 2012), with 41% of these exports going to Canada and 28% going to Uruguay. The trade data for tower exports do not differentiate between tubular towers (primarily used in wind power applications) and other types of towers, unlike the import classification for towers from 2011–2015, which does differentiate. Although some of the tower exports are wind-related, the exact proportion is not known. Other wind turbine component exports are not reported because such exports are likely a small and/or uncertain fraction of broader trade`category totals. Despite overall growth in exports from 2007 to 2014, the United States remained a sizable net importer of wind turbine equipment over this period. The sharp decrease in exports in 2015 may indicate that the fast-rising U.S. wind market absorbed much of the local production of wind turbine equipment.

Figure 15 shows the total value of selected, tracked wind-specific imports to the United States in 2015, by country of origin, as well as the main "districts of entry"[23]: forty percent of the import value in 2015 came from Asia (led by China), 38% from Europe (led by Spain), and 22% from the Americas (led by Brazil). The principal districts of entry for this wind equipment were Houston-Galveston, TX (29%), Great Falls, MT (16%), and Laredo, TX (9%).

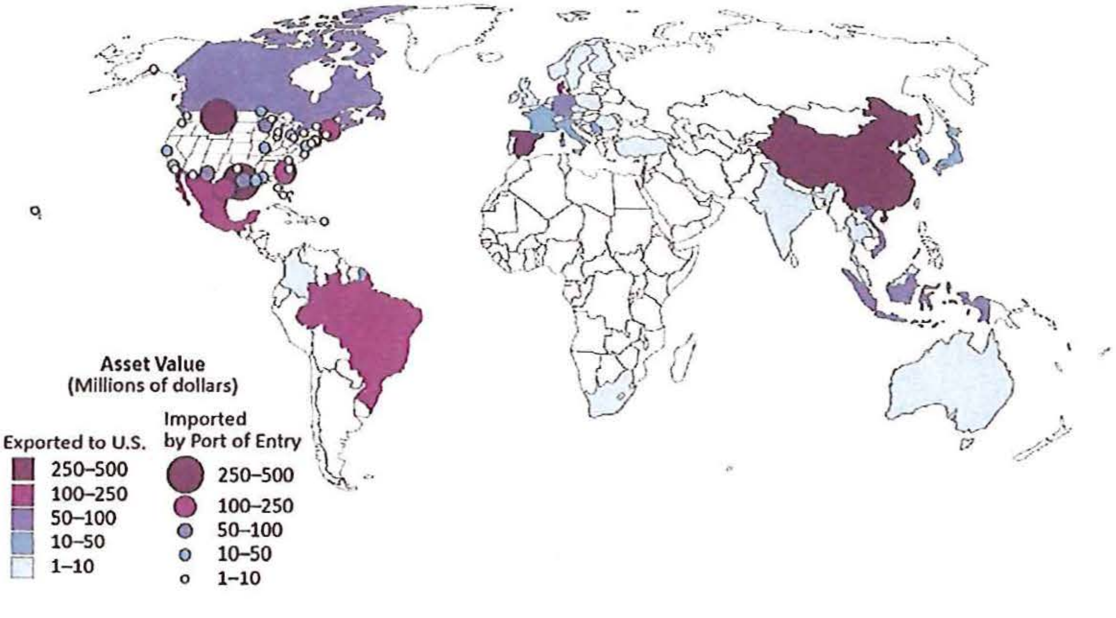


Figure 15. Summary map of tracked wind-specific imports in 2015: countries of origin and U.S. districts of entry

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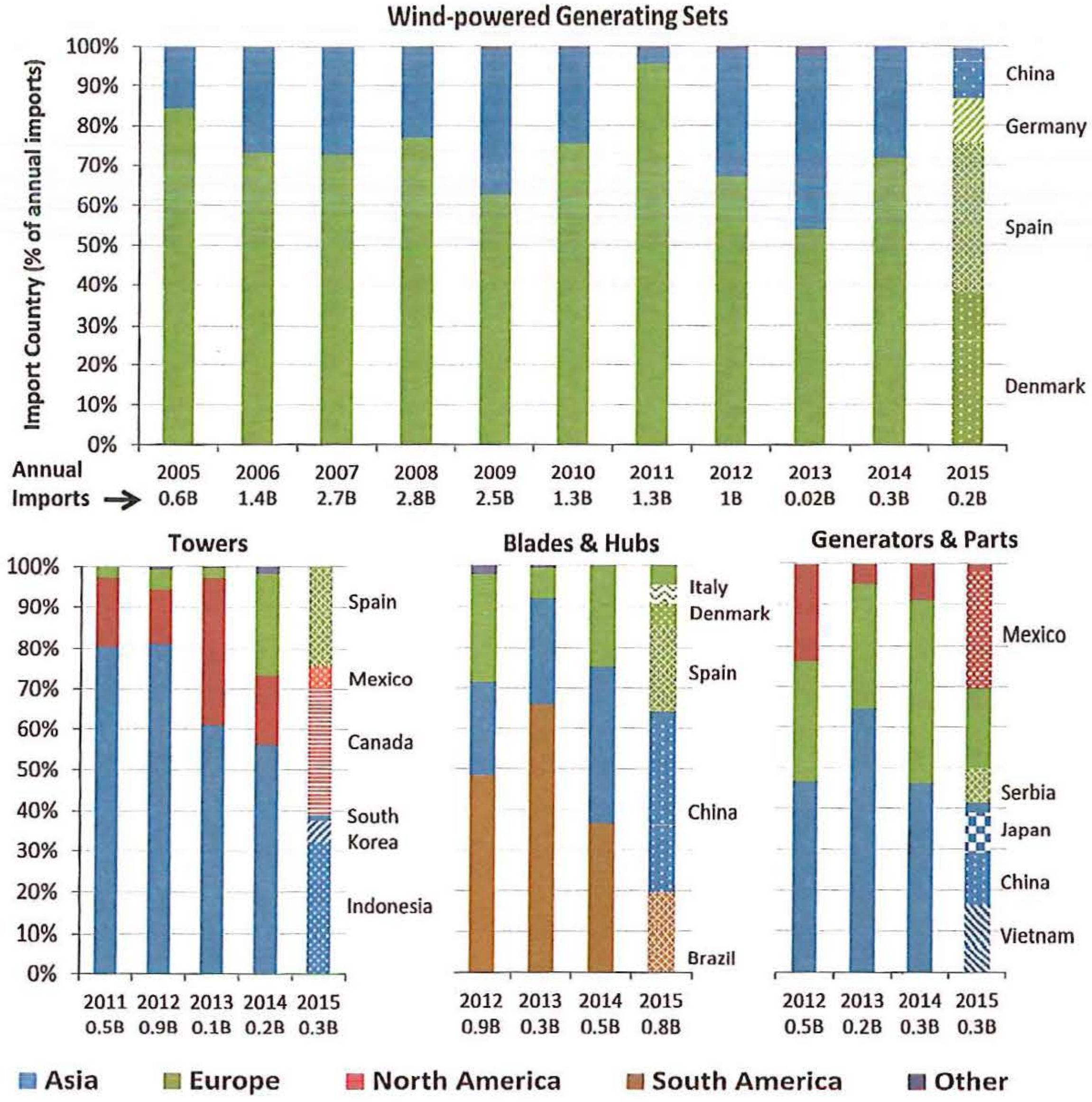
[23] The trade categories included here are all of the wind-specific import categories for 2015 (see the appendix for details), and so the 2015 total import volume considered in Figure 15 differs from that in Figure 14. As noted earlier, imports of many wind turbine component parts occur in broad trade categories not captured by those included in this analysis; additionally, in the case of nacelles without blades, the trade code is not exclusive to wind and so related imports are not included in Figure 15 (though they are included in Figure 14). As such, the data presented in Figure 15 understate the aggregate amount of wind equipment imports into the United States. Note also that "districts of entry" as used here refers to, in some cases, multiple points of entry located in the same geographic region; note also that goods may arrive at districts of entry by land, air, or sea.

Looking behind the import data in more detail, and focusing on those trade codes that are largely exclusive to wind equipment, Figure 16 shows a number of trends over time in the origin of U.S. imports of wind-powered generating sets, tubular towers, wind blades and hubs, and wind generators and parts.



Source: Berkeley Lab analysis of data from USITC DataWeb: http://dataweb.usitc.gov

Figure 16. Origins of U.S. imports of selected wind turbine equipment

For wind-powered generating sets, the primary source markets during 2005–2015 have been Europe and—to a lesser extent—Asia, with leading countries largely being those that are home to the major international turbine manufacturers: Denmark, Spain, Japan, India, and Germany. In 2015, imports of wind-powered generating sets were dominated by Denmark, Spain, Germany, and China, though the total import value was relatively low ($227 million). The share of imports of tubular towers from Asia was over 80% in 2011 and 2012 (almost 50% from China), with much of the remainder from Canada and Mexico. From 2013-2015, not only did the total import value decline relative to earlier years, but there were almost no imports from China and Vietnam—likely a result of the tariff measures that were imposed on wind tower manufacturers from these countries. Tower imports in 2015 came from a mix of countries from Asia (e.g., Indonesia and South Korea), Europe (e.g., Spain), and North America (e.g., Canada and Mexico). With regards to wind blades and hubs, China, Spain, and Brazil dominate as source markets (various other European countries play a somewhat lesser role), with China steadily increasing its market share over time. Finally, the import origins for wind-related generators and generator parts were distributed across a number of largely Asian and European countries, in addition to Mexico, from 2012 through 2015.

Because trade data do not track all imports of wind equipment, it is not possible to use those data to establish a clear overall distinction between import and domestic content. The trade data also do not allow for a precise estimate of the domestic content of specific wind turbine components. Nonetheless, based on those data and a variety of assumptions, Table 4 presents rough estimates of the domestic content for a subset of the major wind turbine components used in U.S. wind power projects in 2015. As shown, domestic content is strong for large, transportation-intensive components such as towers, blades and hubs, and nacelle assembly.

Table 4. Approximate Domestic Content of Major Components in 2015

Towers	Blades & Hubs	Nacelle Assembly
80-85%	50-70%	> 85% of nacelle assembly

These figures, however, understate the wind industry's reliance on turbine and component imports. This is because significant wind-related imports occur under trade categories not captured in Table 4, including wind equipment (such as generator, mainframe, converter, pitch and yaw systems, main shaft, bearings, bolts, controls) and manufacturing inputs (such as foreign steel and oil used in domestic manufacturing).[24]

An alternative interview-based approach to estimating domestic content indicates overall domestic content of all wind turbine equipment used in the United States of about 40% in 2012. When considering balance-of-plant costs as well, overall project-level domestic content in 2012 reached roughly 60%. These interviews further revealed that domestic content is relatively high for blades, towers, nacelle assembly and nacelle covers, supporting the more recent analysis presented in Table 4. The domestic content of most of the equipment internal to the nacelle—much of which is not specifically tracked in wind-specific trade data—is considerably lower, typically well below 20%.[25]

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[24] On the other hand, this analysis also assumes that all components imported into the United States are used for the domestic market and not used to assemble wind-powered generating sets that are exported from the United States. If this were not the case, the resulting domestic fraction would be higher than that presented here.

[25] The interviews and analysis were conducted by GLWN, under contract to Berkeley Lab.

The project finance environment remained strong in 2015

Most of the financing deals that closed in 2015 stemmed from the Tax Increase Prevention Act of 2014, which in late December 2014 extended the PTC's "construction start" deadline for one additional year, from the end of 2013 to the end of 2014 (effectively providing developers with just two weeks during which to start construction in order to qualify for the PTC). Subsequently, in March 2015, the IRS extended its safe harbor guidance for another year as well, enabling wind projects that had met the end-of-2014 construction start deadline to qualify for the PTC (without having to prove continuous effort) if online by the end of 2016.

As a result, 2015 was a big, somewhat rushed year for wind project finance. This was particularly true in the tax equity market, where project sponsors raised anywhere from $5.9 billion (AWEA 2016a) to $6.4 billion (Chadbourne & Parke 2016b) of new tax equity in 2015—up slightly from $5.7-$5.8 billion in 2014 and the largest single-year amount on record. On the debt side, AWEA (2016a) reports that 2,078 MW of new and existing wind capacity raised $2.9 billion in debt in 2015, up from the $2.2 billion raised in 2014, but well below the higher levels seen in previous years when the Section 1603 grant was available.[26] Given the short lead time with the December 2014 PTC extension, most of the projects financed in 2015 will achieve commercial operations in 2016.

As shown in Figure 17, tax equity yields drifted slightly lower in 2015, to just below 8% on an after-tax unlevered basis. Debt interest rates bounced around somewhat, but ultimately headed lower throughout the year, with the 15-year benchmark fixed all-in interest rate starting off 2016 below 4% (~2.5% on a post-tax basis[27]) for the first time in the more-than-eleven-year history of the graph. As a result, the spread between tax equity yields and 15-year term debt (on a post-tax basis) stood at more than 5% as of May 2016—its highest level since 2009. The intransigence of this spread continues to vex those wind project owners that lack tax appetite, and so must finance their projects with relatively expensive tax equity rather than increasingly cheap debt (Chadbourne & Parke 2016a). Partnership flip structures[28] remained the dominant tax equity vehicle, while banks continued to focus more on shorter-duration loans (7–10 year mini-perms

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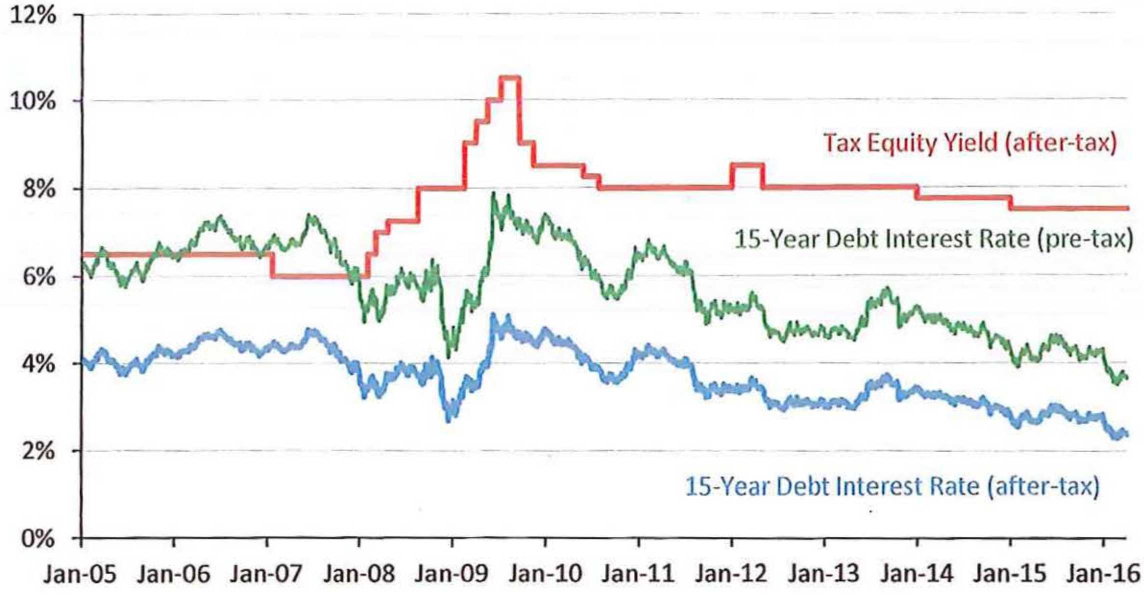
[26] From 2009–2012 (i.e., the years in which the Section 1603 grant was available), some project sponsors who lacked tax appetite financed their projects using the grant in combination with project-level term debt, carrying forward depreciation losses as necessary and foregoing tax equity altogether. With the grant no longer available, most projects now elect the PTC (instead of the ITC), and rely upon third-party tax equity investors to monetize the losses and credits. Because most tax equity investors will not allow leverage on projects in which they invest (Chadbourne & Parke 2016a, 2016b), the expiration of the Section 1603 grant for wind and the correspondingly greater reliance on the PTC could be a contributor to the decline in debt raised by new wind projects in 2013 through 2015.

[27] The returns of equity investors in renewable projects are often expressed on an after-tax basis, because of the significant value that federal tax benefits provide to such projects (e.g., after-tax returns can be higher than pre-tax returns). In order to accurately compare the cost of debt (which is quoted on a pre-tax basis) to tax equity (described in after-tax terms), one must convert the pre-tax debt interest rate to its after-tax equivalent (to reflect the tax-deductibility of interest payments) by multiplying it by 65%, or 100% minus an assumed marginal tax rate of 35%.

[28] A "partnership flip" is a project finance structure in which the developer or project sponsor partners with a third-party tax equity investor to jointly invest in and own the project. Initially, allocations of tax benefits are skewed heavily in favor the tax equity partner (which is able to efficiently monetize the tax benefits), but eventually "flip" in favor of the project sponsor partner once the tax benefits have been largely exhausted. Cash is also allocated between the partners, with one or more "flip" events, but in recent years has been increasingly directed towards the project sponsor to the extent possible, in order to support back leverage or dividend payments to YieldCo investors.

remained the norm[29]), leaving longer-duration, fully amortizing loans to institutional lenders (Chadbourne & Parke 2016b).



Source: Federal Reserve Board (2016), Bloomberg NEF (2016e)

Figure 17. Cost of 15-year debt and tax equity for utility-scale wind projects over time

Looking ahead, financing in both the tax equity and debt markets is likely to remain active in 2016 and beyond, thanks to the five-year tax credit extension (with phase down) that became law in late December 2015 (see Chapter 8, Policy and Market Drivers, for more details on this long-term extension and phase-down). In May 2016, the IRS also increased the safe harbor window from two years to four years, effectively allowing a wind project that starts construction before the end of 2016 and achieves commercial operations before the end of 2020 to qualify for the PTC at full value. The tax credit will progressively diminish for projects that start construction in 2017-2019 (and that achieve commercial operations from 2021-2023), which suggests that 2016 and 2017 could represent the peak of project finance activity for the foreseeable future (see pages 68-69 for a lengthier discussion of the PTC phase down schedule).

IPPs own the vast majority of wind assets built in 2015

Independent power producers (IPPs) own 7,290 MW or 85% of the 8,598 MW of new wind capacity installed in the United States in 2015 (Figure 18). More than 1,000 MW are owned by investor-owned utilities (IOUs), including MidAmerican (502 MW), Xcel Energy (350 MW), Montana-Dakota Utilities (107.5 MW), and Northwestern Energy (80 MW), while publicly

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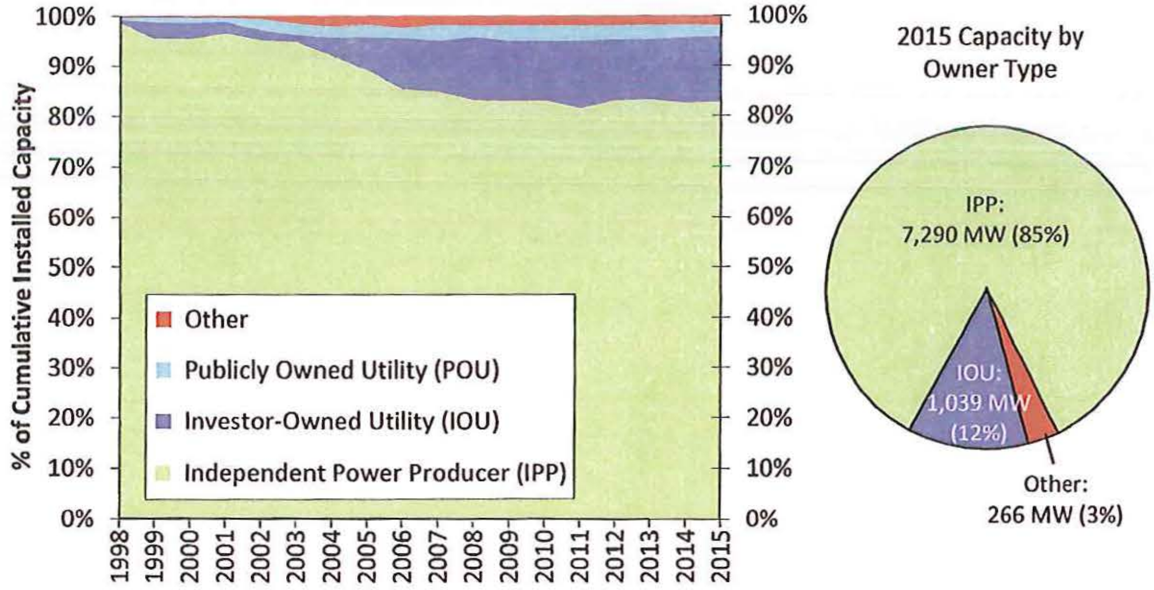
[29] A "mini-perm" is a relatively short-term (e.g., 7–10 years) loan that is sized based on a much longer tenor (e.g., 15–17 years) and therefore requires a balloon payment of the outstanding loan balance upon maturity. In practice, this balloon payment is often paid from the proceeds of refinancing the loan at that time. Thus, a 10-year mini-perm might provide the same amount of leverage as a 17-year fully amortizing loan but with refinancing risk at the end of 10 years. In contrast, a 17-year fully amortizing loan would be repaid entirely through periodic principal and interest payments over the full tenor of the loan (i.e., no balloon payment required and no refinancing risk).

owned utilities (POUs) do not own any of the new wind power capacity brought online in 2015. Finally, 266 MW (3%) fall into the "other" category of projects owned by neither IPPs nor utilities (e.g., towns, schools, businesses, farmers); notably, IKEA owns most of this capacity (263 MW) through two wind projects – one in Illinois and one in Texas.[30] Of the cumulative installed wind power capacity at the end of 2015, IPPs own 83% and utilities own 15% (13% IOU and 2% POU), with the remaining 2% falling into the "other" category.



Source: Berkeley Lab estimates based on AWEA project database

Figure 18. Cumulative and 2015 wind power capacity categorized by owner type

Long-term contracted sales to utilities remained the most common off-take arrangement, but direct retail sales gained ground

Electric utilities continued to be the dominant off-takers of wind power in 2015 (Figure 19), either owning (12%) or buying (48%) power from 60% of the new capacity installed last year (with the 60% split between 37% IOU and 23% POU). On a cumulative basis, utilities own (15%) or buy (53%) power from 68% of all wind power capacity installed in the United States (with the 68% split between 48% IOU and 20% POU).

Merchant/quasi-merchant projects accounted for 29% of all new 2015 capacity and 24% of cumulative capacity. Merchant/quasi-merchant projects are those whose electricity sales revenue is tied to short-term contracts and/or wholesale spot electricity market prices (with the resulting

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[30] Many of the "other" projects, along with some IPP- and POU-owned projects, might also be considered "community wind" projects that are owned by or benefit one or more members of the local community to a greater extent than typically occurs with a commercial wind project. According to AWEA (2016a), just 16.9 MW (0.2%) of 2015 wind capacity additions qualified as community wind projects.

price risk commonly hedged over a 10- to 12-year period[31]) rather than being locked in through a long-term PPA.

Perhaps the biggest story of 2015 with respect to off-take agreements was the rise of direct retail purchasers of wind (and solar) power, including both corporate and non-corporate off-takers, which together are characterized in Figure 19 as "direct retail" off-takers. Though barely visible in the cumulative portion of Figure 19, direct retail purchases accounted for 844 MW or 10% of the new wind power capacity installed in the United States in 2015. This modest 10% portion is well below the 52% of total wind capacity contracted through PPAs in 2015 that involve non-utility buyers, as reported by AWEA (2016a). The difference is that the 10% pertains to projects that achieved commercial operation in 2015, whereas the 52% pertains to PPAs that were executed in 2015—in many cases for projects that will come online in 2016 or 2017 (or beyond). According to AWEA (2016a), this 52% is up from 23% in 2014 and just 5% in 2013, suggesting that the direct retail segment of Figure 19 should continue to expand in future years.

Power marketers are defined here to include commercial intermediaries that purchase power under contract and then resell that power to others.[32] Though power marketers were very active throughout the first decade of this century following the initial wave of electricity market restructuring, their influence has waned in recent years: just 6% of cumulative wind power capacity in the United States sells to power marketers, down from more than 20% in the early 2000s.

Finally, just 3 MW (0.0%) of the wind power additions in 2015 that used turbines larger than 100 kW were interconnected on the customer side of the utility meter, with the power being consumed on site rather than sold.

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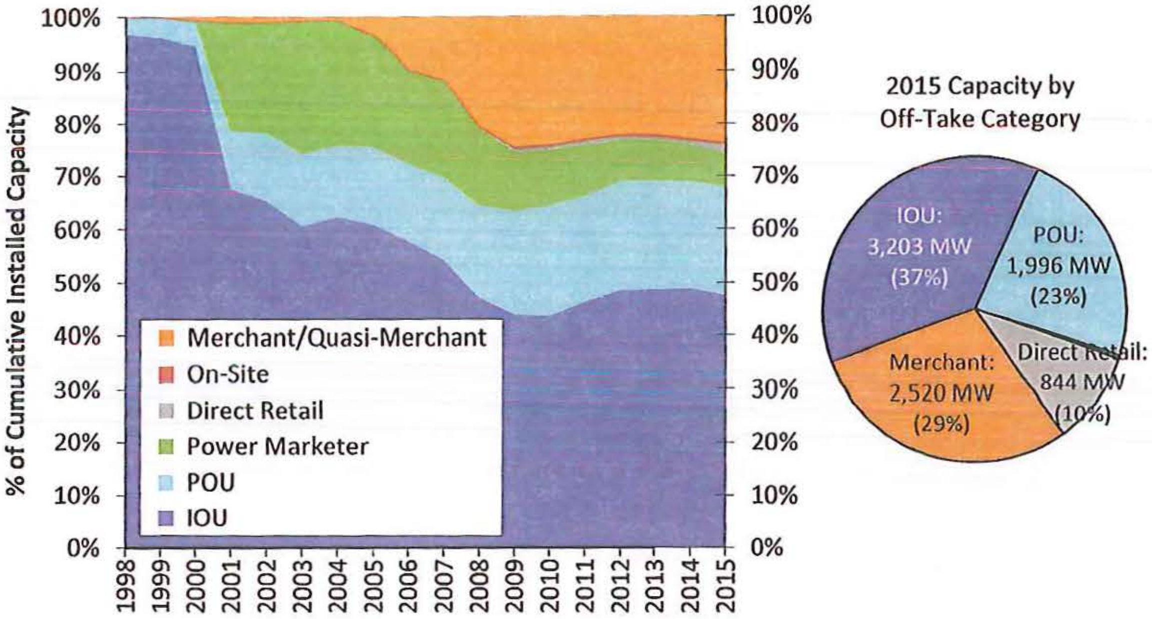
[31] Hedges are often structured as a "fixed-for-floating" power price swap—a purely financial arrangement whereby the wind power project swaps the "floating" revenue stream that it earns from spot power sales for a "fixed" revenue stream based on an agreed-upon strike price. For some projects, the hedge is structured in the natural gas market rather than the power market.

[32] These intermediaries include the wholesale marketing affiliates of large IOUs, which may buy wind on behalf of their load-serving affiliates.



Source: Berkeley Lab estimates based on AWEA project database

Figure 19. Cumulative and 2015 wind power capacity categorized by power off-take arrangement

4. Technology Trends

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

The average nameplate capacity of the newly installed wind turbines in the United States in 2015 was 2.0 MW, up 180% since 1998–1999 (Figure 20).[33] The average hub height of turbines installed in 2015 was 82.0 meters, up 47% since 1998–1999. Average rotor diameters have increased at a more rapid pace than hub heights in the United States, especially in recent years. The average rotor diameter of wind turbines installed in 2015 was 102.0 meters, up 113% since 1998–1999, which translates into a 355% growth in rotor swept area. These trends in hub height and rotor scaling are two of several factors impacting the project-level capacity factors highlighted later in this report.

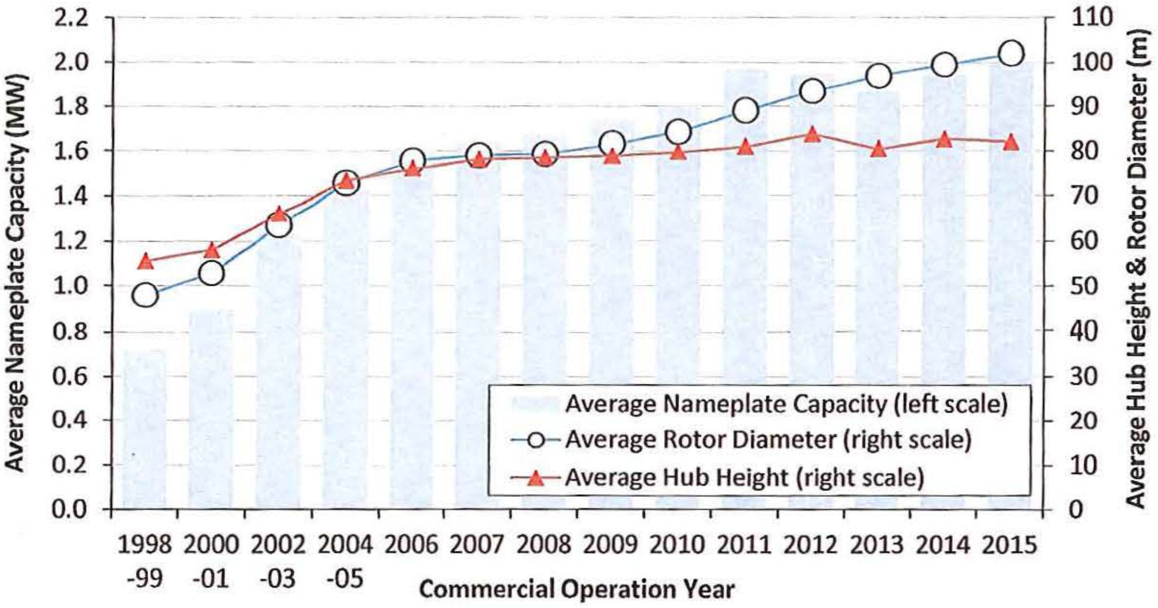


Figure 20. Average turbine nameplate capacity, rotor diameter, and hub height installed during period

Growth in rotor diameter has outpaced growth in nameplate capacity and hub height in recent years

As indicated in Figure 20, and as detailed in Figures 21–23, rotor diameter scaling has been especially significant over the last six years—more so than increases in nameplate capacity and hub heights, both of which have seen a stabilization of the long-term trend in recent years.

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[33] Figure 20 (as well as a number of the other figures and tables included in this report) combines data into both 1- and 2-year periods in order to avoid distortions related to small sample size in the PTC lapse years of 2000, 2002, and 2004; although not a PTC lapse year, 1998 is grouped with 1999 due to the small sample of 1998 projects. Though 2013 was a slow year for wind additions, it is shown separately here despite the small sample size.

Starting with turbine nameplate capacity, Figure 21 presents not only the trend in average nameplate capacity (as also shown earlier, in Figure 20) but also how the prevalence of different turbine capacity ratings has changed over time. The average nameplate capacity of newly installed wind turbines has largely held steady since 2011, and the longer-term pace of growth started to slow after 2006. While it took just six years (2000–2005) for MW-class turbines to almost totally displace sub-MW-class turbines, it took another seven years (2006–2012) for multi-MW-class turbines (i.e., 2 MW and above) to gain nearly equal market share with MW-class turbines. The years 2013 and 2014 showed some reversal of that trend, but 2015 was the first year in which > 2 MW turbines were the majority of those installed.

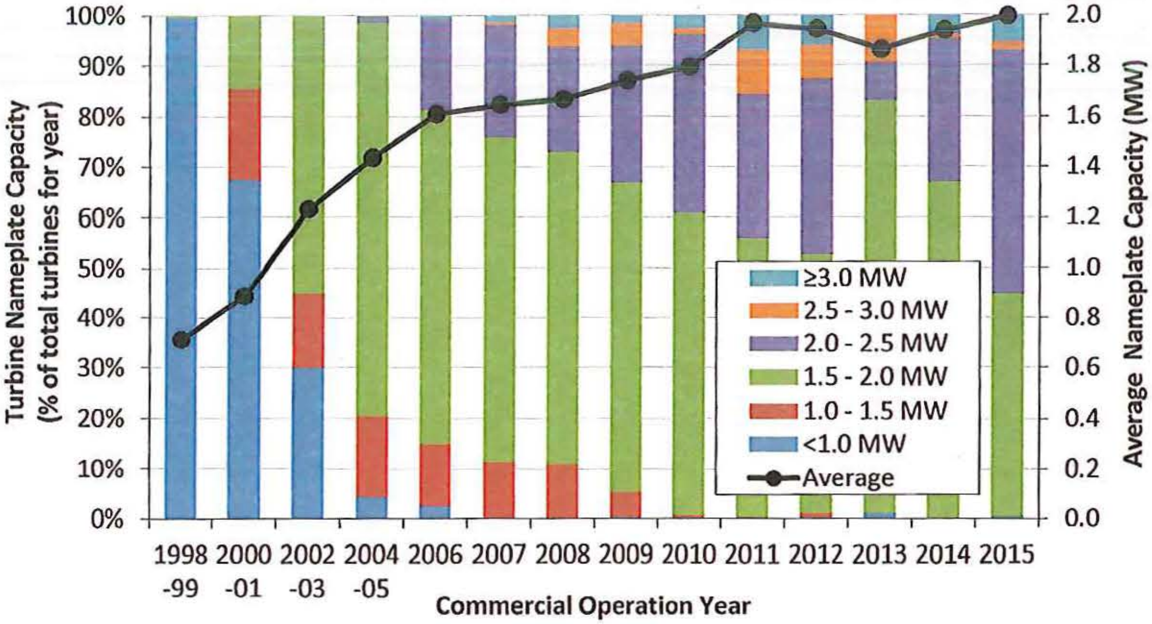

Figure 21. Trends in turbine nameplate capacity

As with nameplate capacity, the average hub height of wind turbines has largely held constant since 2011 (Figure 22). More generally, growth in average hub height has been slow since 2005, with 80 meter towers dominating the overall market. Towers that are 90 meters and taller started to penetrate the market in 2011, however, a trend that has remained steady into 2015, equating to roughly 15% of the market in that year. Finally, although we saw the emergence of >100 meter towers as early as 2007, that segment of the market peaked in 2012 when 16% of newly installed turbines were taller than 100 meters; since 2012, only 1% or less of newly installed turbines in each year (including 2015) have featured towers that tall.

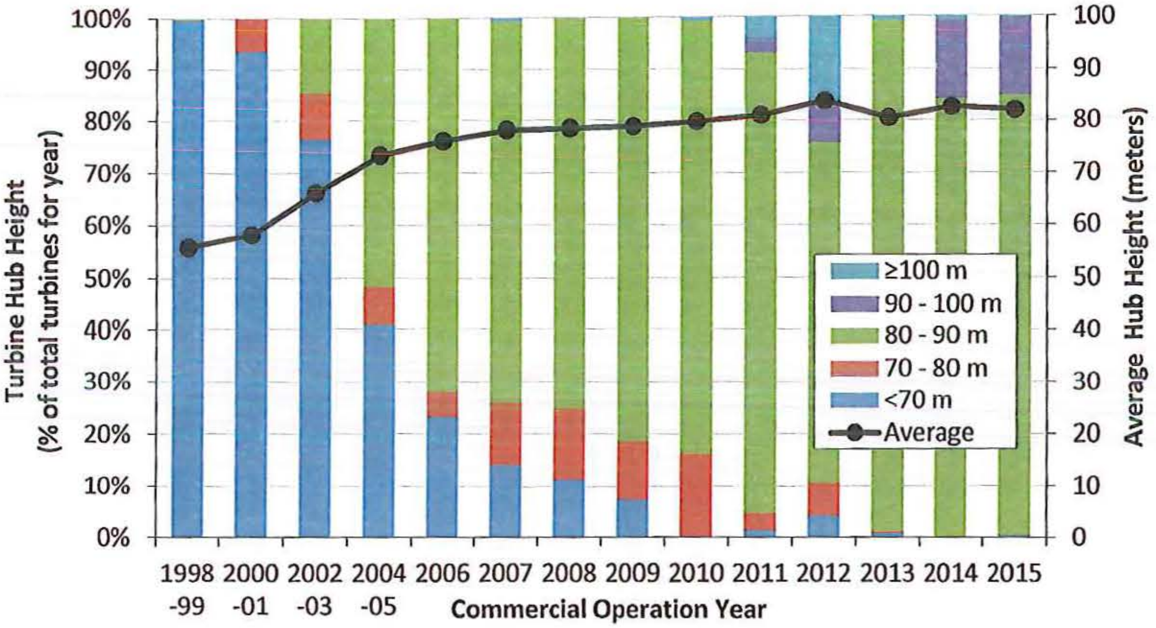

Figure 22. Trends in turbine hub height

The movement towards larger-rotor machines has dominated the U.S. industry in recent years, with OEMs progressively introducing larger-rotor options for their standard turbine offerings and introducing new turbines that feature larger rotors, despite steady average nameplate capacity (Figure 21) and hub heights (Figure 22). As shown in Figure 23, this recent increase has been especially apparent since 2009. In 2008, no turbines employed rotors that were 100 meters in diameter or larger. By 2012, 47% of newly installed turbines featured rotors of at least that diameter, and in 2015 the percentage grew to 86%. Rotor diameters of 110 meters or larger, meanwhile, started penetrating the market in 2012; in 2015, 20% of newly installed turbines featured rotors of that size.

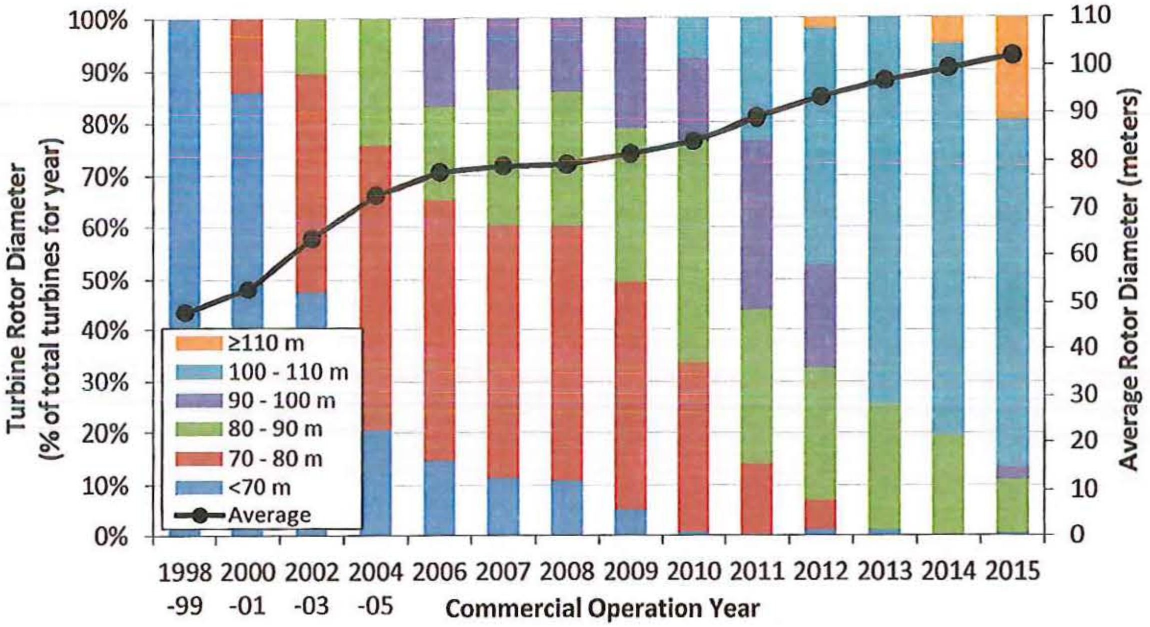

Figure 23. Trends in turbine rotor diameter

Turbines originally designed for lower wind speed sites have rapidly gained market share

Though trends in the average nameplate capacity, hub height, and rotor diameter of turbines have been notable, the growth in the swept area of the rotor has been particularly rapid. With growth in average swept area (in m^2) outpacing growth in average nameplate capacity (in W), there has been a decline in the average "specific power" (in W/m^2) among the U.S. turbine fleet over time, from 394 W/m^2 among projects installed in 1998–1999 to 246 W/m^2 among projects installed in 2015 (Figure 24). The decline in specific power was especially rapid from 2001 to 2005 and, more recently, from 2011 to 2015.

All else equal, a lower specific power will boost capacity factors, because there is more swept rotor area available (resulting in greater energy capture) for each watt of rated turbine capacity, meaning that the generator is likely to run closer to or at its rated capacity more often. In general, turbines with low specific power were originally designed for lower wind speed sites; they were intended to maximize energy capture in areas where the wind resource is modest, and where large rotor machines would not be placed under undue physical stress. As suggested in Figure 24 and as detailed in the next section, however, such turbines are now in widespread use in the United States—even in sites with high wind speeds. The impact of lower specific-power turbines on project-level capacity factors is discussed in more detail in Chapter 5.

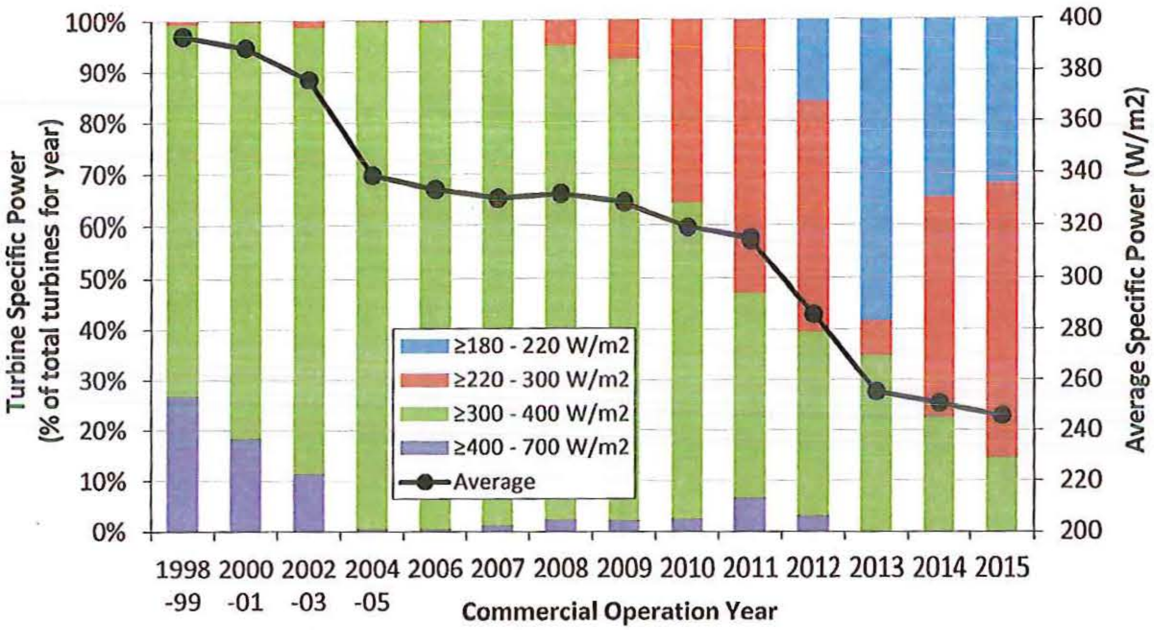

Figure 24. Trends in turbine specific power

Another indication of the increasing prevalence of machines initially designed for lower wind speeds is revealed in Figure 25, which presents trends in wind turbine installations by IEC Class. The IEC classification system considers multiple site characteristics, including wind speed, gusts, and turbulence. Class 3 turbines are generally designed for lower wind speed sites (7.5 m/s and below), Class 2 turbines for medium wind speed sites (up to 8.5 m/s), and Class 1 turbines for higher wind speed sites (up to 10 m/s). Some turbines are designed at the margins of two classifications, and are labeled as such (e.g., Class 2/3). Additionally, 9% of the turbines installed in 2015 were Class S, which is outside IEC rating system.[34]

The U.S. wind market has clearly become increasingly dominated by IEC Class 3 turbines in recent years. In 2000–2001, Class 1 machines were prevalent. From 2002 through 2011, Class 2 machines dominated the market. Since 2011, there has been a substantial decline in the use of Class 2 turbines, and a concomitant increasing market share of Class 3 and Class 2/3 turbines. In 2015, 55% of the newly installed turbines were Class 3 machines, 33% were Class 2/3 machines, and less than 3% of turbines were Class 2 or lower.

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[34] The IEC 61400 Class "S" turbines in 2015 were GE Wind 1.7 MW turbines with 103 meter rotors on 80 meter towers, installed in five states. These turbines are not included in the reported average IEC class over time.

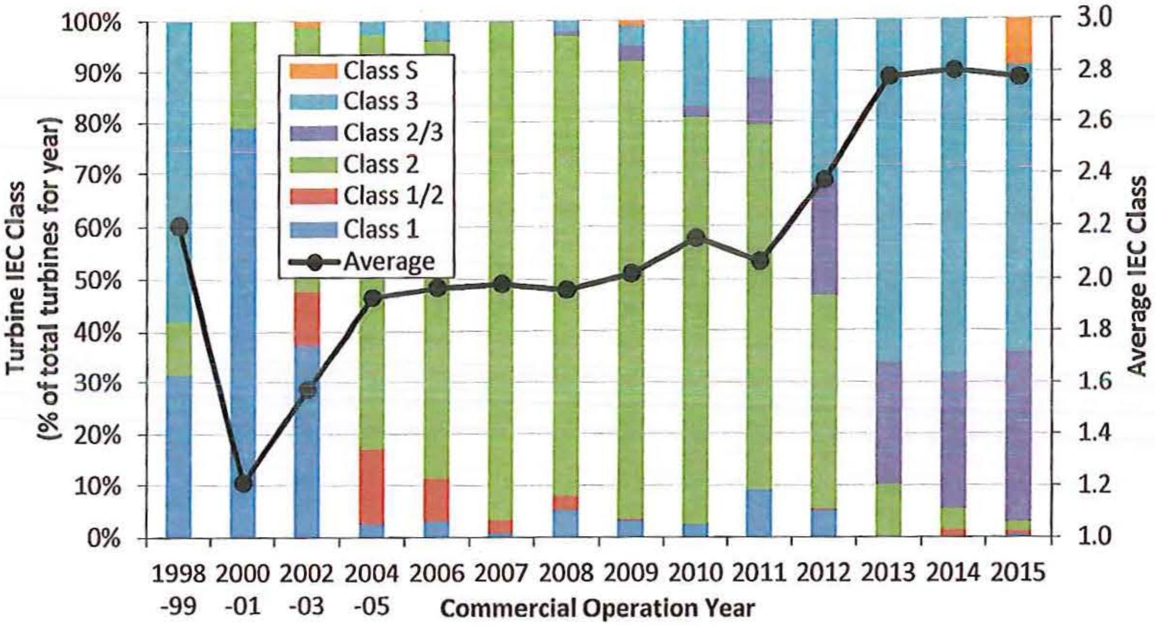

Figure 25. Trends in turbine IEC class

Moreover, Class 2, 2/3, and 3 turbine technology has not remained stagnant. Figure 26 shows the trend in average specific power across all turbines installed in each year (regardless of IEC Class, matching the average line shown in Figure 24) and also the average specific power ratings of Class 2, 2/3, and 3 (i.e., medium and lower wind speed) turbines installed in the United States. Through 2011, the progressively lower specific power of Class 2 turbines, which dominated the market, drove the overall decline in fleet-wide specific power. Since 2012, though, the continued drop in fleet-wide specific power has been driven by the penetration of the even-lower specific power of Class 3 and Class 2/3 machines. The overall trend in fleet-wide specific power has, therefore, been driven not only by the increased penetration of, initially, Class 2 and then, later, Class 2/3 and 3 turbines, but also by the progressively lower specific power ratings of turbines within each of these IEC classes.[35]

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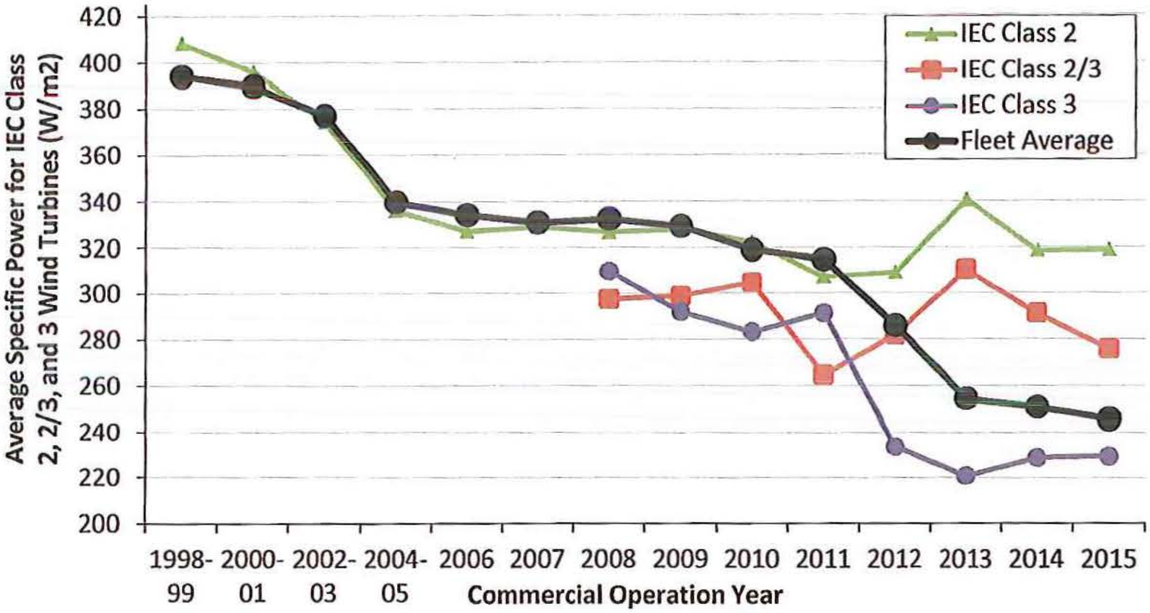
[35] The average specific power for the Class S turbines installed in 2015 was 205 W/m^2, which further drove down the fleet-wide average for specific power in 2015.



Note: specific power averages are shown only for years where there were at least 40 turbines in the respective IEC Class

Figure 26. Trends in specific power for IEC class 2, 2/3, and 3 turbines installed in the U.S.

Turbines originally designed for lower wind speeds are now regularly employed in both lower and higher wind speed sites; taller towers predominate in the Great Lakes and Northeast

One might expect that the increasing market share of turbines designed for lower wind speeds would be due to a movement by wind developers to deploy turbines in lower wind speed sites. Though there is some evidence of this movement historically (see Chapter 5), it is clear in Figures 27 and 28 that turbines originally designed for lower wind speeds are now regularly employed in all regions of the United States, and in both lower and higher wind speed sites.

Figure 27 presents the percentage of turbines installed in four distinct regions of the United States[36] (see Figure 29 for regional definitions) that have one or more of the following three attributes: (a) a higher hub height, (b) a lower specific power, and (c) a higher IEC Class. It focuses solely on turbines installed in the 2012–2015 time period. Figure 28 presents similar information, but segments the data by the wind resource quality of the site rather than by the region in which the turbines are located.

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[36] Due to very limited sample size, we exclude the Southeast region from these graphs and related discussion.

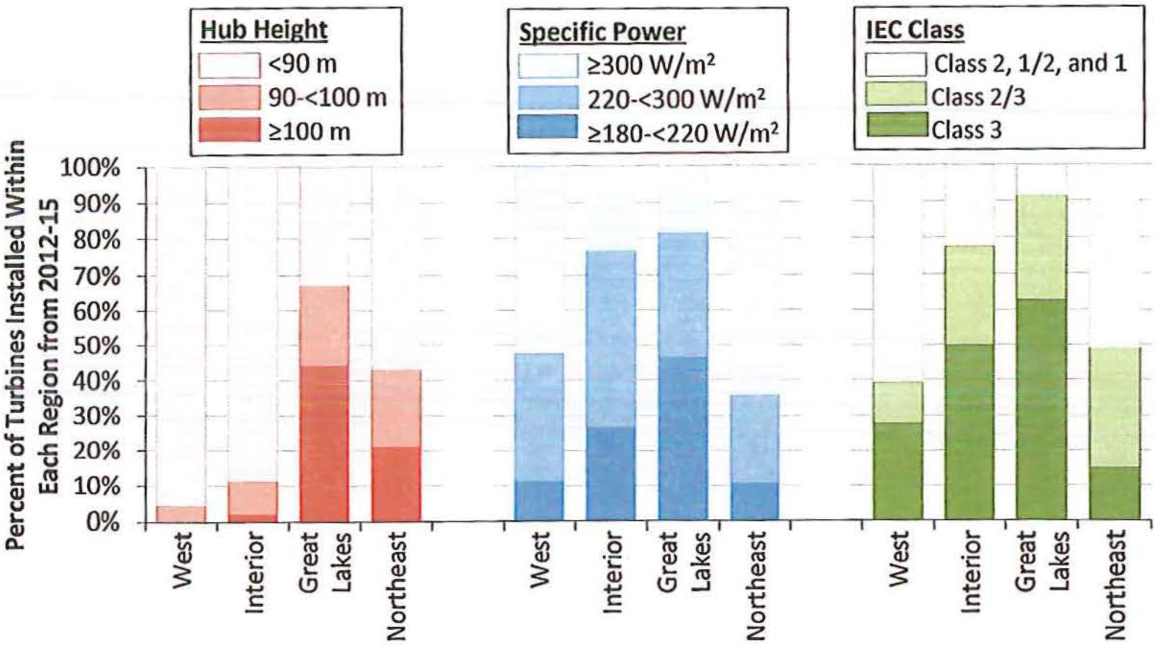
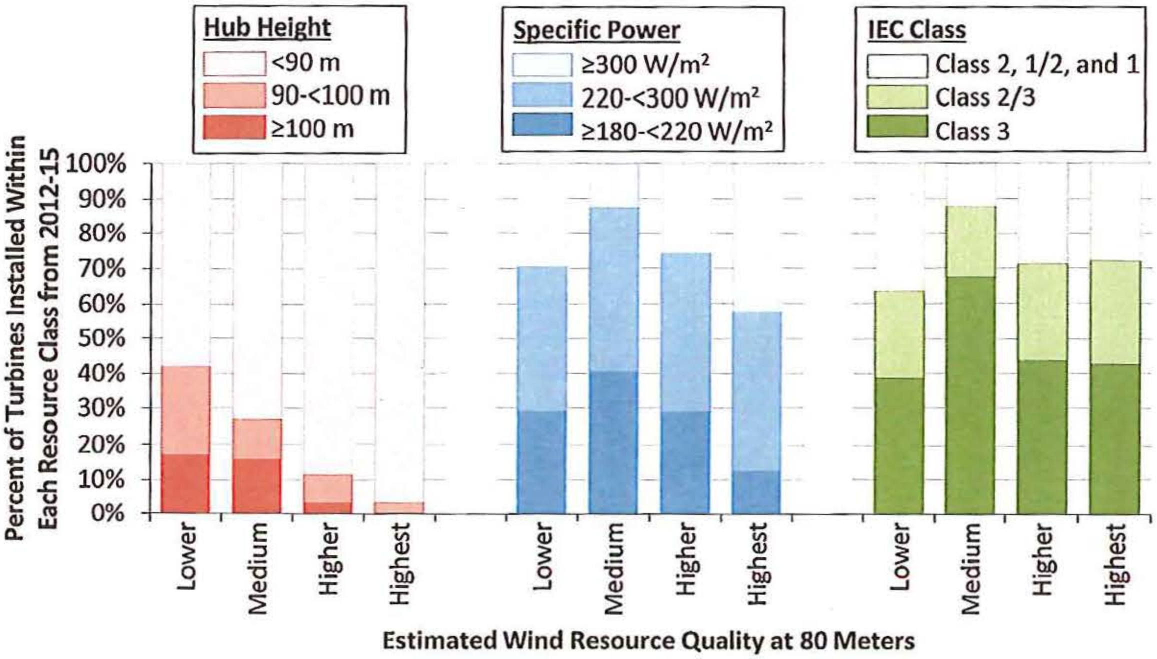


Figure 27. Deployment of turbines originally designed for lower wind speed sites, by region



Note: Wind resource quality is based on site estimates of gross capacity factor at 80 meters by AWS Truepower. The "lower" category includes all projects with an estimated gross capacity factor of <40%, the "medium" category corresponds to 40%–45%, the "higher" category corresponds to 45%-50%, and the "highest" category includes any project at or exceeding 50%.

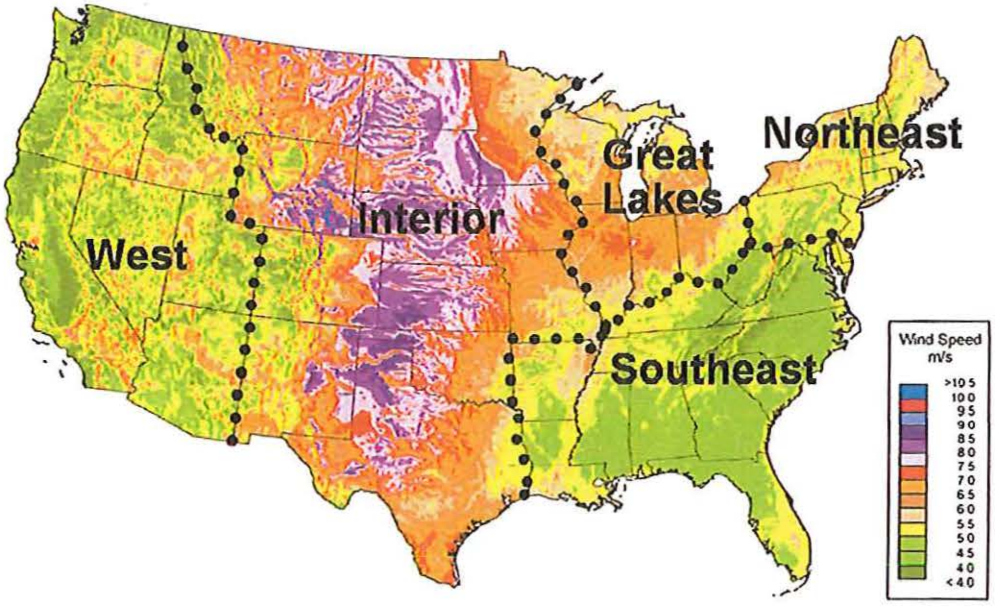
Figure 28. Deployment of turbines originally designed for lower wind speed sites, by estimated wind resource quality

Taller towers (i.e., 90 meters and above) have seen higher market share in the Great Lakes (67%) and Northeast (43%) than in the Interior (11%) and West (4%), often in sites with lower wind speeds. This is largely due to the fact that such towers are most commonly used in sites with higher-than-average wind shear (i.e., greater increases in wind speed with height) to access the better wind speeds that are typically higher up. Sites with higher wind shear are prevalent in the Great Lakes and Northeast.

Low specific power machines installed over this four-year period have been regularly deployed in all regions of the country, though their market share in the Great Lakes (81%) and Interior (77%) exceeds that in the West (48%) and Northeast (36%). Similarly, these turbines have been commonly used in all resource regimes including at sites with very high wind speeds, as shown in Figure 28. Turbines with the lowest specific power ratings (180–220 W/m^2), however, have been installed in greater proportions at lower, medium, and higher wind speed sites than at the highest wind speed sites, and are more prevalent in the Great Lakes.

Turning to IEC Class, we see a somewhat similar story. Over this period, Class 3 and Class 2/3 machines have had the largest market share in the Great Lakes (91%) and Interior (78%) regions, but have also gained significant market in the Northeast (49%) and West (39%). Moreover, these turbines have been regularly deployed in both lower- and higher-quality resources sites.

In combination, these findings demonstrate that low specific power and Class 3 and 2/3 turbines, originally designed for lower wind speed sites, have established a strong foothold across the nation and over a wide range of wind speeds. In many parts of the Interior region, in particular, relatively low wind turbulence has allowed turbines designed for low wind speeds to be deployed across a wide range of site-specific resource conditions.



Source: AWS Truepower, National Renewable Energy Laboratory

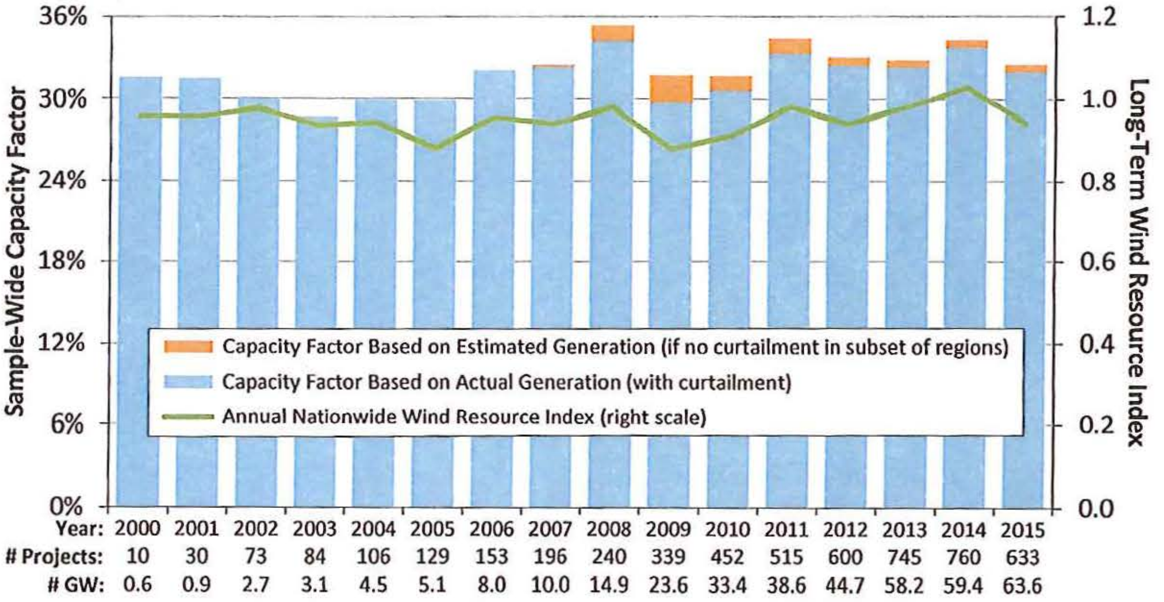
Figure 29. Regional boundaries overlaid on a map of average annual wind speed at 80 meters

5. Performance Trends

Following the previous discussion of technology trends, this chapter presents data from a Berkeley Lab compilation of project-level capacity factors. The full data sample consists of 633 wind projects built between 1998 and 2014 totaling 63,556 MW (96.5% of nationwide installed wind capacity at the end of 2014).[37] Excluded from this assessment are older projects, installed prior to 1998. The discussion is divided into three subsections: the first analyzes trends in sample-wide capacity factors over time; the second looks at variations in capacity factors by project vintage; and the third focuses on regional variations. Unless otherwise noted, all capacity factors in this chapter are reported on a net (i.e., taking into account losses from curtailment, less-than-full availability, wake effects, icing and soiling, etc.) rather than gross basis.

Sample-wide capacity factors have gradually increased, but have been impacted by curtailment and inter-year wind resource variability

The blue bars in Figure 30 show the average sample-wide capacity factor of wind projects in each calendar year among a progressively larger cumulative sample in each year, focusing on projects installed from 1998 through 2014.[38]



Source: Berkeley Lab

Figure 30. Average cumulative sample-wide capacity factors by calendar year

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[37] Although some performance data for wind power projects installed in 2015 are available, those data do not span an entire year of operations. As such, for the purpose of this section, the focus is on projects with commercial operation dates from 1998 through 2014.

[38] There are fewer individual projects—although more capacity—in the 2015 cumulative sample than there are in 2014. This is due to the sampling method used by EIA, which focuses on a subset of larger projects throughout the year, before eventually capturing the entire sample some months after the year has ended. As a result, it might be late 2016 before EIA reports 2015 performance data for all of the wind power projects that it tracks, and in the meantime this report is left with a smaller sample consisting mostly of the larger projects in each state.

Viewed this way—on a cumulative, sample-wide basis—one might expect to see a gradual improvement in capacity factor over time, as newer turbines with taller towers and lower specific power are added to the fleet. In general, the data support this trend; capacity factors averaged 32.8% between 2011 and 2015 versus 31.8% between 2006 and 2010 versus 30.3% between 2000 and 2005. However, several factors influence the apparent strength of this time-based trend. Two of those factors are discussed below—wind energy curtailment and inter-year variability in the strength of the wind resource. Two additional factors—the average quality of the resource in which projects are located and performance degradation as projects age—are discussed in the next section.

Wind Power Curtailment. Curtailment of wind project output can occur due to transmission inadequacy, minimum generation limits, other forms of grid inflexibility, and/or environmental restrictions—all but the last of which could help to push local wholesale power prices negative, thereby potentially triggering curtailment for economic reasons, particularly among wind projects that do not receive the PTC. Curtailment might be expected to increase as wind energy penetrations rise. That said, in areas where curtailment has been particularly problematic in the past—principally in Texas—steps taken to address the issue have significantly mitigated the concern. For example, Figure 31 shows that only 1.0% of potential wind energy generation within ERCOT was curtailed in 2015, down sharply from 17% in 2009, roughly 8% in both 2010 and 2011, and nearly 4% in 2012. Primary causes for the decrease were the Competitive Renewable Energy Zone transmission line upgrades, most of which were completed by the end of 2013, and a move to more-efficient wholesale electric market designs.

Elsewhere, the only regions shown in Figure 31 in which wind curtailment exceeded 1% in 2015 were MISO at 5.4% (as much of the new wind buildout continues to be located within this ISO) and ISO-NE at 2.4% (a rough estimate that the grid operator suspects is understated). Except for BPA, all of the regions shown in Figure 31 track both "forced" (i.e., required by the grid operator for reliability reasons) and "economic" (i.e., voluntary as a result of wholesale market prices) curtailment. BPA (which did not report in 2014 or 2015) tracks only forced curtailment, which means that its modest curtailment estimates for 2010–2013 may understate the true level of curtailment experienced by wind power projects in the region.

In aggregate, assuming a 33% average capacity factor, the total amount of curtailed wind generation tracked in Figure 31 for 2015 equates to the annual output of roughly 1,125 MW of wind power capacity. Looked at another way, wind power curtailment has reduced sample-wide average capacity factors in recent years. While the blue bars in Figure 30 reflect actual capacity factors—i.e., including the negative impact of curtailment events—the orange bars add back in the estimated amount of wind generation that has been forced to curtail in recent years within the seven areas shown in Figure 31, to estimate what the sample-wide capacity factors would have been absent this curtailment. As shown, sample-wide capacity factors would have been on the order of 0.5–2 percentage points higher nationwide from 2008 through 2015 absent curtailment in just this subset of regions. Estimated capacity factors would have been even higher if comprehensive forced and economic curtailment data were available for all regions.[39]

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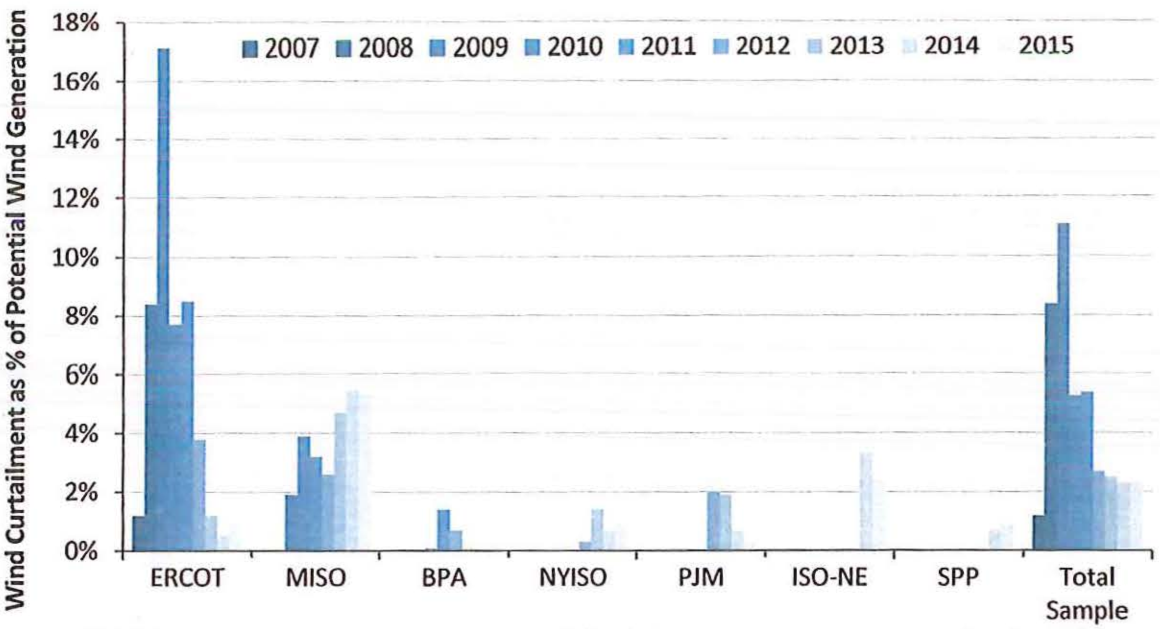
[39] Excluding BPA (for which 2015 data were not available), the six regions included in Figure 31 collectively contributed 72% of total U.S. wind generation in 2015.



Note: BPA's 2014 and 2015 curtailment estimates were unavailable at the time of publication. A portion of BPA's curtailment from 2010-13 is estimated assuming that each curtailment event lasts for half of the maximum possible hour for each event. SPP's 2014 curtailment estimate is for March through December only. PJM's 2012 curtailment estimate is for June through December only. Except for BPA, which tracks only forced curtailment, all other percentages shown in the figure represent both forced and economic curtailment.

Source: ERCOT, MISO, BPA, NYISO, PJM, ISO-NE, SPP

Figure 31. Estimated wind curtailment by region as a percentage of potential wind generation

Inter-Year Wind Resource Variability. The strength of the wind resource varies from year to year, partly in response to significant persistent weather patterns such as El Niño/La Niña. A relatively strong El Niño had a significant impact in the first two quarters of 2015, contributing to wind speeds that were significantly below normal throughout much of the U.S. Although wind speeds recovered in the third and fourth quarters, annual average deviations of 6% or more for all of 2015 were common, particularly in the West and southern Great Plains states, where much of the wind capacity in the U.S. is located (AWS Truepower 2016).

The green line in Figure 30 also shows that 2015 was generally a bad wind year, at least in terms of the national average wind energy resource as measured by one large project sponsor.[40] It is also evident from the figure that movements in sample-wide capacity factor from year to year are influenced by the natural inter-year variability in the strength of the national wind resource.

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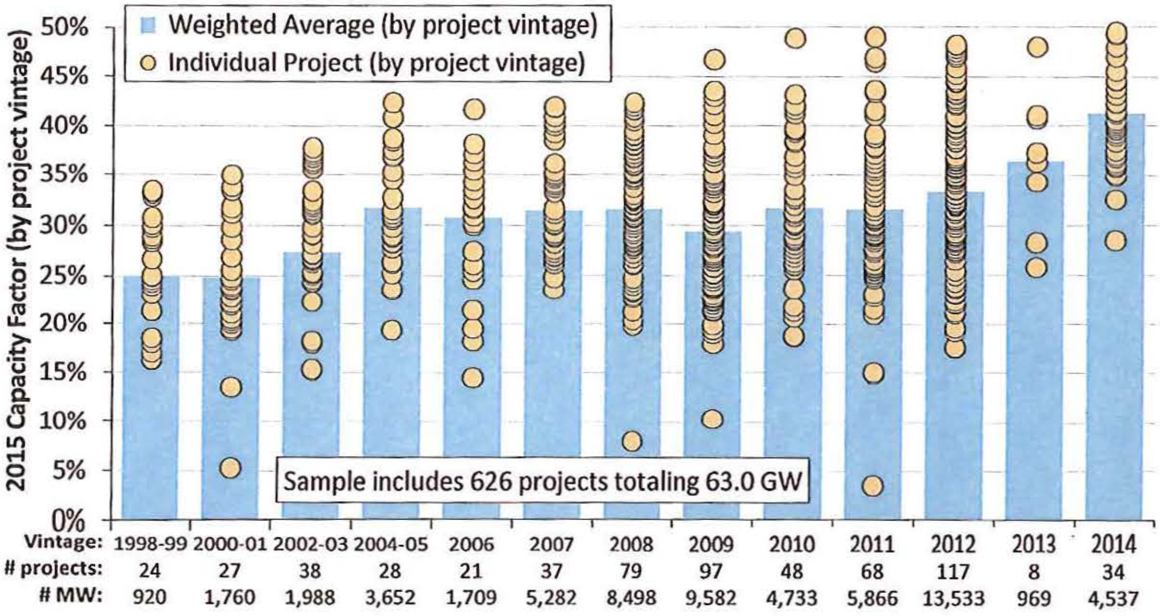
[40] The green line in Figure 30 estimates changes in the strength of the average nationwide wind resource from year to year and is derived from data presented by NextEra Energy Resources in its quarterly earnings reports.

The impact of technology trends on capacity factor becomes more apparent when parsed by project vintage

One way to partially control for the time-varying influences described in the previous section (e.g., annual wind resource variations or changes in the amount of wind curtailment) is to focus exclusively on capacity factors in a single year, such as 2015.[41] As such, while Figure 30 presents sample-wide capacity factors in each calendar year, Figure 32 instead shows only capacity factors in 2015, broken out by project vintage. Wind power projects built in 2015 are again excluded, as full-year performance data are not yet available for those projects.

Figure 32 shows an increase in weighted-average 2015 capacity factors when moving from projects installed in the 1998–1999 period to those installed in the 2004–2005 period. Subsequent project vintages through 2011, however, show little if any improvement in average capacity factors recorded in 2015. This pattern of stagnation is finally broken by projects installed in 2012, and even more so by 2013- and 2014-vintage projects. The average 2015 capacity factor among projects built in 2014 reached 41.2%, compared to an average of 31.2% among all projects built from 2004–2011, and 25.8% among all projects built from 1998–2003.



Source: Berkeley Lab

Figure 32. Calendar year 2015 capacity factors by project vintage

The trends in average capacity factor by project vintage seen in Figure 32 can largely be explained by three underlying influences shown in Figure 33: a trend towards progressively lower specific power ratings (note that Figure 33 actually shows the inverse of specific power, so

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[41] Although focusing just on 2015 does control (at least loosely) for some of these known time-varying impacts, it also means that the *absolute* capacity factors shown in Figure 32 may not be representative over longer terms if 2015 was not a representative year in terms of the strength of the wind resource (as mentioned above, it was not – wind speeds were well below normal across much of the U.S. in 2015) or wind power curtailment.

that a declining specific power is correlated directionally with a higher capacity factor) and higher hub heights—both of which should boost capacity factors, all else equal—as well as a progressive build-out of lower-quality wind resource sites through 2012 (which should hurt capacity factors, all else equal), followed by deployment at more energetic sites in 2013 and 2014. In addition, as shown later in Figure 36, project vintage itself could be a fourth driver, given the possible degradation in performance among older projects.

The first two of these influences—the decline in average "specific power" (i.e., W/m^2 of rotor swept area) and the increase in average hub height among more recent turbine vintages—have already been well-documented in Chapter 4, but are shown yet again in Figure 33 (again, with specific power shown in inverse form, to correlate with capacity factor movements) in index form, relative to projects built in 1998-99. All else equal, a lower average specific power will boost capacity factors, because there is more swept rotor area available (resulting in greater energy capture) for each watt of rated turbine capacity, meaning that the generator is likely to run closer to or at its rated capacity more often. Meanwhile, at sites with positive wind shear, increasing turbine hub heights can help the rotor to access higher wind speeds.

Counterbalancing the decline in specific power and the increase in hub height, however, has been a tendency to build new wind projects in lower-quality wind resource areas,[42] at least through 2012—and especially among projects installed from 2009 through 2012[43]—as shown by the wind resource quality index in Figure 33. This trend reversed course in 2013 and even more so in 2014, as deployment increasingly shifted to the Interior region.

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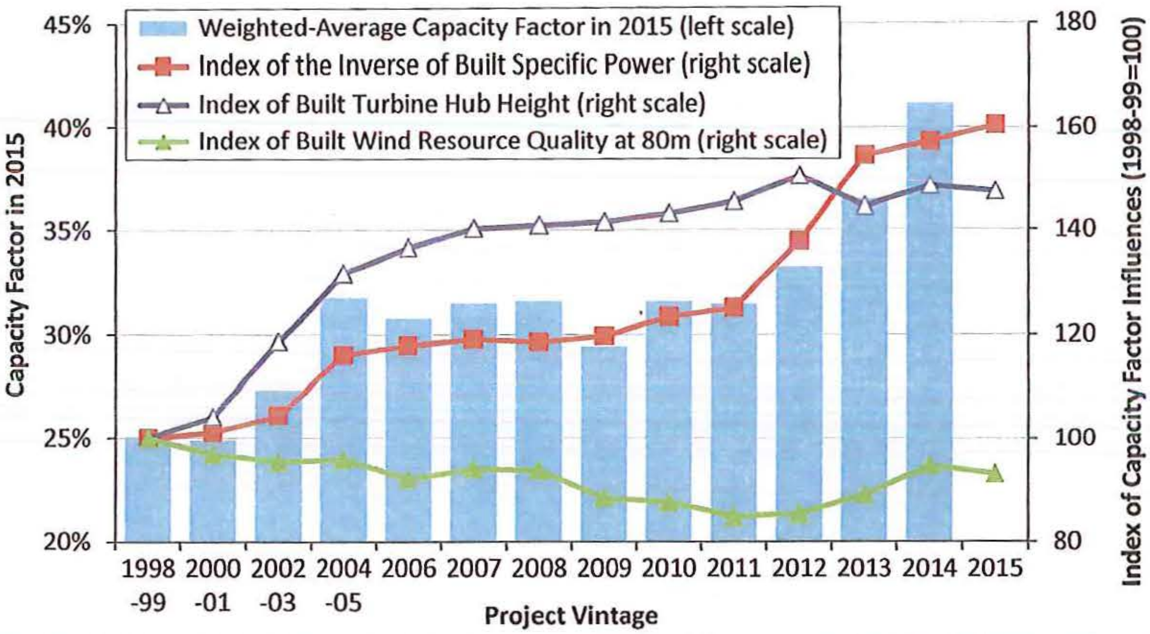
[42] Estimates of wind resource quality are based on site estimates of *gross* capacity factor at 80 meters, as derived from nationwide wind resource maps created for NREL by AWS Truepower. We index the values to those projects built in 1998-99. Further details are found in the Appendix.

[43] Several factors could have driven this trend, especially in the 2009 to 2012 period. First, the increased availability of low-wind-speed turbines that feature higher hub heights and a lower specific power may have enabled the economic build-out of lower-wind-speed sites. Second, developers may have reacted to increasing transmission constraints over this period (or other siting constraints, or even just regionally differentiated wholesale electricity prices) by focusing on those projects in their pipeline that may not be located in the best wind resource areas but that do have access to transmission (or higher-priced markets, or readily available sites without long permitting times). Finally, federal and/or state policy could be partly responsible. For example, wind projects built in the 4-year period from 2009 through 2012 were able to access a 30% cash grant (or ITC) in lieu of the PTC. Because the dollar amount of the grant (or ITC) was not dependent on how much electricity a project generates, it is possible that developers seized this limited opportunity to build out the less-energetic sites in their development pipelines. Additionally, state RPS requirements sometimes require or motivate in-state or in-region wind development in lower wind resource regimes.



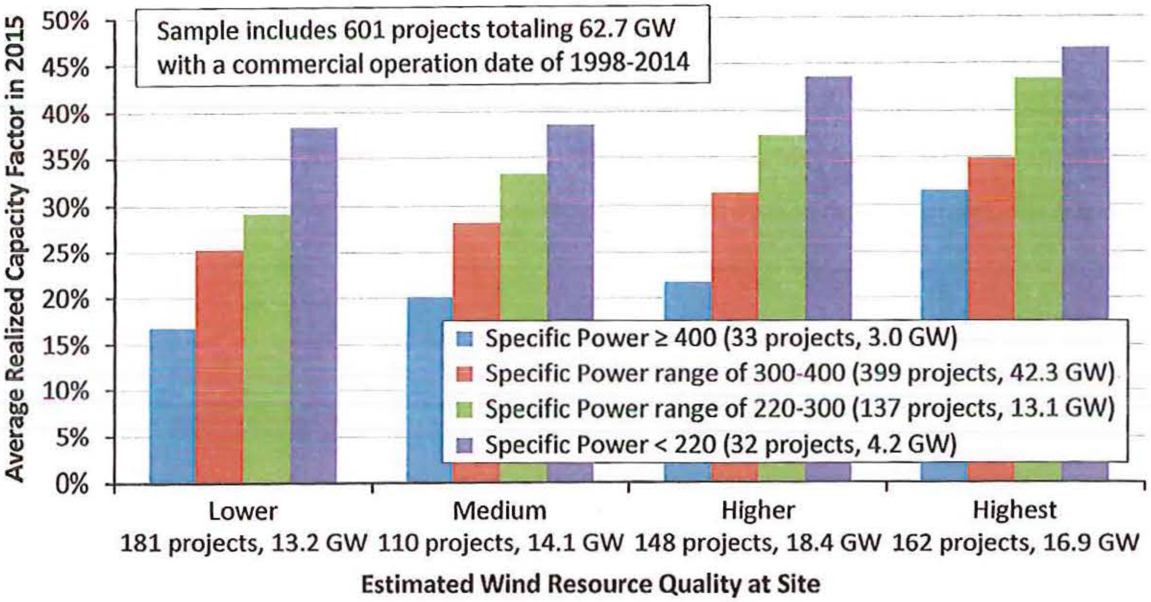
Note: In order to have all three indices be directionally consistent with their influence on capacity factor, this figure indexes the inverse of specific power (i.e., a decline in specific power causes the index to increase rather than decrease).

Source: Berkeley Lab

Figure 33. 2015 capacity factors and various drivers by project vintage

In Figure 33, the significant improvement in average 2015 capacity factors from those projects built in 1998-2001 to those built in 2004-2005 is driven by both an increase in hub height and a decline in specific power, and despite a shift towards somewhat-lower-quality wind resource sites. The stagnation in average capacity factor that subsequently persisted through 2011-vintage projects reflects relatively flat trends in both hub height and specific power, coupled with an ongoing decline in wind resource quality at built sites. Finally, capacity factors began to move higher among 2012-vintage projects, and continued even higher among 2013- and 2014-vintage projects, driven by a sharp reduction in average specific power coupled with a marked improvement in the quality of wind resource sites (average hub height stayed relatively constant over this period). Looking ahead to 2016, 2015-vintage projects are likely to perform similarly to those built in 2014 on average, given only modest changes in these three underlying drivers among the 2015 fleet.

To help disentangle the competing influences of turbine design evolution and lower wind resource quality on capacity factor, Figure 34 controls for each. Across the x-axis, projects are grouped into four different categories, depending on the wind resource quality estimated for each site. Within each wind resource category, projects are further differentiated by their specific power. As one would expect, projects sited in higher wind speed areas generally realized higher 2015 capacity factors than those in lower wind speed areas, regardless of specific power. Likewise, within each of the four wind resource categories along the x-axis, projects that fall into a lower specific power range realized significantly higher 2015 capacity factors than those in a higher specific power range.



Note: Wind resource quality is based on site estimates of gross capacity factor at 80 meters by AWS Truepower. The "lower" category includes all projects with an estimated gross capacity factor of <40%, the "medium" category corresponds to 40%–45%, the "higher" category corresponds to 45%-50%, and the "highest" category includes any project at or exceeding 50%.

Source: Berkeley Lab

Figure 34. Calendar year 2015 capacity factors by wind resource quality and specific power

As a result, it is clear that turbine design changes (specifically, lower specific power, but also, to a lesser extent, higher hub heights) are driving realized capacity factors higher among projects located within a given wind resource regime. This finding is further illustrated in Figure 35, which again groups projects into the same four different categories of wind resource quality, and then reports average realized 2015 capacity factors by commercial operation date within each category.[44] As before, projects sited in higher wind speed areas have, on average, higher capacity factors. More importantly, although there is some variability in the year-to-year trends, it is clear that within each of the four wind resource categories there has been an improvement in capacity factors over time, by commercial operation date.

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[44] The figure only includes those data points representing at least three projects in any single resource-year pair. Among 2013-vintage projects, only the "lower" wind resource quality grouping meets this sample size threshold. In addition, the "medium" wind resource quality grouping lacks sufficient sample size in both 2006 and 2014. In years where insufficient sample size prohibits the inclusion of a data point, dashed lines are used to interpolate from the prior year to the subsequent year.