Chapter 2

Wind Vision:

A New Era for Wind Power in the United States

U.S. DEPARTMENT OF ENERGY


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2 Wind Power in the United States:

Recent Progress, Status Today, and Emerging Trends

Summary

With more than 61 gigawatts (GW) installed across 39 states at the end of 2013, wind power has confirmed its credibility as a scalable, reliable and environmentally sound energy technology, and a cost-effective source of low emissions power generation in those regions of the United States in which substantial wind potential exists. The United States has more than 15,000 GW of technical[1] wind resource potential, both land-based and offshore, that can be harnessed and delivered reliably into existing power networks through utility-scale and distributed installations [1]. U.S. wind generation was entirely land-based technology as of 2013. The U.S. Department of Energy (DOE) recognizes, however, that offshore wind has become prominent in Europe—reaching 6.5 GW through year-end 2013 [2]—and could emerge in the United States in the near future. Nearly all scales of wind power technology are reflected in the *Wind Vision* study,[2] although distributed wind applications are captured primarily within the larger land-based designation.[3] In this chapter, offshore and distributed wind technologies are highlighted in Sections 2.2 and 2.3, respectively.

U.S. electricity demand served by wind power has tripled since 2008, increasing from 1.5% of total end-use demand to 4.5%[4] in 2013 [3]. Trends indicate that continued and increased wind deployment can have significant and wide-ranging positive effects for the nation's energy mix and environmental goals, while at the same time creating jobs and economic development activities associated with wind deployment and equipment manufacturing. These resources and trends—combined with cost reductions, technology advances, increased industry collaboration, and improved reliability—provide the foundation for the *Wind Vision Study Scenario,* introduced in Chapter 1 and summarized in Chapter 3, Text Box 3-2.

Wind power has become an established, reliable contributor to the nation's electricity supply. It provides affordable, clean domestic energy as part of a portfolio of sustainable power generation options.

Wind technology improvements have evolved to make lower wind speed sites[5] more economically viable even in regions previously thought to have limited wind potential, such as the Southeast. Despite deployment growth, technology enhancements, and cost reductions, however, wind power expansion continues to be affected by energy demand, transmission and integration limitations, fluctuations in raw material costs, policy uncertainty, conflicting uses, siting concerns, and competition with other energy sources such as natural gas.

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1. The National Renewable Energy Laboratory (NREL) routinely estimates the technical potential of specific renewable electricity generation technologies. These are technology-specific estimates of energy generation potential based on renewable resource availability and quality, technical system performance, topographic limitations, environmental, and land-use constraints only. The estimates do not consider (in most cases) economic or market constraints, and therefore do not represent a level of renewable generation that might actually be deployed. *www.nrel.gov*
2. Wind turbines can range in sizes from small 1 kW machines to multi-MW offshore turbines. The *Wind Vision* primarily focuses on centralized power generation that utilizes utility-scale (1MW+) land-based and offshore wind turbines.
3. Distributed wind is the use of wind turbines at homes, farms and ranches, businesses, public and industrial facilities, off-grid, and other sites connected either physically or virtually on the customer side of the meter. These turbines are used to offset all or a portion of local energy consumption at or near those locations, or are connected directly to the local grid to support grid operations. Distributed wind systems can range in size from a 1-kilowatt or smaller off-grid wind turbine at a remote cabin to a 10-kilowatt turbine at a home or agricultural load to several multi-megawatt wind turbines at a university campus, manufacturing facility, or any large energy user.
4. The *Wind Vision* metric for the share of wind in a given year is calculated using data published by the EIA, as total net wind generation divided by total annual electricity retail sales. This ratio is 4.5% for 2013 and is consistent with the definitions for the future wind penetration levels in the *Wind Vision Study Scenario* as noted in Chapter 1.
5. In *Wind Vision*, 'lower wind speed sites' are those with average wind speeds less than 7.5 meters per second [m/s] at hub height. In the International Electrotechnical Commission (IEC) turbine classification system this is equivalent to IEC Class 3 or higher turbine class.

2.0 Introduction

This chapter summarizes the state of wind power as of year-end 2013 across a number of aspects, including wind power markets and economics; economic and social impacts, including workforce development and environmental effects; wind resource characterization; wind technology and performance; supply chain, manufacturing, and logistics; wind integration and delivery; wind siting, permitting, and deployment; and collaboration, education, and outreach. More recent data for 2014 may be available but were excluded due to publication schedule requirements. The special issues surrounding offshore wind and distributed wind are also presented. This compilation characterizes the trends influencing formation of the *Wind Vision Study Scenario* (Chapter 3) and aligns them to roadmap activities described in Chapter 4. The following is a short summary of key points in this chapter.

Wind Power Markets and Economics

Investments in wind manufacturing and deployment continue to support industry growth. According to the United Nations Environment Programme, global investment in wind power grew from $14 billion in 2004 to $80 billion in 2013, a compound annual growth rate of 21% [4, 5].[6] Domestic manufacturing for many wind components is strong largely because of this investment trend, technical advancements that have helped make wind viable even in lower resource areas, and increased domestic demand for wind power. The combined import share of selected wind equipment tracked by trade codes (i.e., blades, towers, generators, gearboxes, and complete nacelles), when presented as a fraction of total equipment-related turbine costs, declined from roughly 80% in 2006–2007 to 30% in 2012–2013 [6]. The share of wind turbine project costs, including non-turbine equipment project costs that were sourced domestically, was approximately 60% in 2012 [6]. In 2013, the wind supply chain included more than 560 facilities across 43 states [7]. Given the transport and logistics challenges of moving large wind turbine components over long distances, continued U.S. manufacturing and supply chain vitality is expected to be at least partially coupled to future levels of domestic demand for wind equipment. Recent fluctuations in demand and market uncertainty have forced some manufacturing facilities to furlough employees and others to cease operations altogether.

The levelized cost of electricity (LCOE) is the present value of total costs incurred to deliver electricity to the point of grid connection, divided by the present value of energy production over a defined duration. In effect, LCOE is the cost of generating electricity from a specific source—over an assumed financial lifetime—that allows recovery of all project expenses and meets investor return requirements. LCOE provides an economic assessment of the cost of the energy-generating system including all costs over its lifetime: initial investment, operations, and maintenance; cost of fuel; and cost of capital.

In sites with higher wind speeds,[7] the LCOE of wind declined by more than 33% from 2009–2013, and, in some markets, wind power sales prices are competitive with traditional fossil generation [6]. Significant variations, however, are seen in the LCOE of individual wind projects. The LCOE for wind is influenced by capital and balance of system costs, operations and maintenance (O&M) costs, financing costs, and project performance. Incentives and policies also have significant effects on project-specific LCOE, most notably for wind project development costs and power purchase agreement (PPA) terms.

Installation rates for wind projects are affected by overall electricity demand, wholesale power prices, and state and federal policies. A national boom in natural gas reserves has created some uncertainties for wind power in the near term. The Energy Information Administration (EIA) confirmed 29% of the nation's electric power as coming from natural gas in 2012. This trend fell to 26% in 2013, but natural gas still exerted downward pressure on wholesale power prices. At the same time, overall energy demand since 2008 has remained constant due to a stagnant economy coupled with energy efficiency improvements—thus reducing overall growth for electricity generation technologies, including wind.

6. Unless otherwise specified, all financial results reported in this chapter are in 2013$.

7. In the *Wind Vision,* 'higher wind speed sites' are those with average wind speeds of 7.5 meters per second [m/s] or higher at hub height. In the International Electrotechnical Commission (IEC) turbine classification system this is equivalent to IEC Class 2 or 1 turbine classes.

Economic and Social Impacts

Operating experience and research demonstrate that the current and potential social benefits of wind power are wide-ranging and significant. For example, a 2012 study evaluating county-level economic development effects in counties with wind development determined that wind power installations between 2000 and 2008 increased county-level personal income by approximately $11,000 for every megawatt (MW) of installed capacity [8]. These estimates translate to a median increase in total county personal income and employment of 0.2% and 0.4% for counties with installed wind power over the same period. Similarly, a 2011 study in four rural counties in western Texas found total economic activity in local communities to be nearly $730 million over the assumed 20-year life cycle of the plants, or $520,000 (2011$) per MW of installed capacity. These economic benefits derive from increased personal income and reduced electric rates; temporary and permanent employment in construction, engineering, transportation, manufacturing, and operations; local economic activity resulting from wind construction; and increased revenues from land lease payments and tax revenue. Nationally, wind power projects delivered at least $180 million annually to local landowners through lease payments in 2013 [9].

In addition to significant economic and employment-related benefits, wind deployment also offers health and environmental benefits including reduced greenhouse gas (GHG) emissions; reduced harmful air pollutants such as sulfur dioxide (SO_2), nitrogen oxide (NO_x), and particle matter; and reduced water use. Wind power in the United States in 2013 was estimated to have reduced direct power-sector carbon dioxide (CO_2) emissions by 115 million metric tonnes (127 million short tons), equivalent to eliminating the emissions of 20 million cars during the year. An estimated 157,000 metric tonnes (173,000 short tons) of SO_2 emissions and 97,000 metric tonnes (107,000 short tons) of NO_x were avoided due to the wind power generated in 2013. Wind power generation in 2013 is estimated to have reduced power-sector water consumption by 36.5 billion gallons, or roughly 116 gallons per person in the United States [10].

Wind Technology and Performance, Supply Chain, Manufacturing, and Logistics

Continued advancements in land-based turbines and offshore wind technologies enhance wind power opportunities in every geographic region of the United States. Progress has been made to improve performance and reliability and reduce the cost of individual wind turbines. Enhancements have included design of longer blades and taller towers that capture more energy from the wind, developments in drive train designs, and use of improved controls and sensors. By 2013, focus began shifting from individual turbine performance to overall system performance characteristics.

Technology advancements center on developing enhanced micro-siting strategies and complex control systems for arrays of wind turbines. These enhanced technologies broaden the range of viable wind sites by facilitating greater energy capture at high wind speeds as well as economical energy capture at lower wind speeds. A better understanding of the wind resource and continued technology developments are leading trends in improved performance, increased reliability, and reduced cost of wind electricity. Additionally, declining wind power costs are driving domestic demand for wind power, wind industry jobs, and economic growth in all regions of the country. As turbine multi-MW wind technology advances and components like blades and towers increase in size, however, transportation costs could increase and manufacturing may become more complex.

Based on installation experience gained between 2006 and 2013, expanded domestic manufacturing will not be constrained by raw materials availability or manufacturing capability. Reductions in demand for wind power, however, will channel resources to other industries and could slow a return to high levels of wind deployment [11]. Equipment and skilled labor availability will continue to be dependent on near-term domestic demand. Continued innovation in turbine design, manufacturing, transportation, and construction can help the industry overcome logistical barriers and improve international competitiveness.

Wind Integration and Delivery

Wind power has become a major contributor to electricity supply in the nation and around the world. U.S. electric power networks have operated reliably with high wind contributions of 10% and higher on an annual basis, with minimal impacts on network operating costs. Power system operators experienced with wind now view wind generation routinely as a dependable component of their portfolio of generating options. Nine U.S. states are currently operating with greater than 12% of their annual electricity generation from wind (Colorado, Idaho, Iowa, Kansas, Minnesota, North Dakota, Oklahoma, Oregon, and South Dakota), with two of them (Iowa and South Dakota) operating with greater than 25% of in-state generation from wind [7].

Large amounts of wind have been and continue to be reliably and effectively integrated into electric power systems, but many sites with wind power resources have minimal or no access to electrical transmission facilities. This hurdle is a bottleneck to cost-effective wind deployment, and additional transmission system expansion is needed for higher wind penetration levels [9]. Concerted effort has yielded progress nationally in addressing transmission and interconnection barriers, and curtailment[8] has been reduced from its peak in 2009 [6]. Siting, planning, and cost-allocation issues remain barriers to transmission investment for wind and other forms of generation, but dedicated efforts continue to yield progress in addressing these concerns.

Wind turbine technology has evolved to incorporate more direct drive technology, which has been relatively slow to enter the U.S. market features. New grid-friendly features have evolved, such as low-voltage ride-through. This feature allows wind turbines to stay online during low-voltage events, contributing to system stability. In addition, frequency response—the ability of the wind turbine to increase or decrease generation to help support nominal system frequency of 60 Hertz—is now a feature of modern wind turbines. The ability to respond to automatic generator control signals, or AGC, allows wind turbines to provide regulation service—system balancing on very short time scales from about 4 seconds to several minutes, depending on the region. Finally, simulated inertial response provides fast response during a disturbance.

Wind Siting, Permitting, Deployment, and Collaboration

As of 2013, both the processes and information requirements for permitting wind projects vary across applications (land-based, offshore, and distributed) as well as across geographic boundaries (locate, state and federal). This lack of uniformity in the regulatory environment can lead to uncertainties in project development timelines and success.

Industry experience and research have improved understanding of wind power's impacts to wildlife and local communities. Progress has been made through careful siting, public engagement, and mitigation strategies. While improvements have been made with respect to understanding impacts and identifying effective mitigation strategies, however, continued research is needed to further understand the true nature and extent of wildlife impacts. The focus is on co-existence—addressing community and regulatory concerns while maximizing wind power opportunities. Open collaboration with the community and its leaders increases public involvement and comprehension about best practices to manage social impacts for both offshore and land-based wind developments. Offshore wind is still in early development phases, but significant progress is being made to facilitate siting, leasing, and construction of offshore wind power projects in both federal and state waters.

A number of government agencies, industry organizations, researchers and academia, non-government organizations (NGOs), and collaborative groups such as the American Wind Wildlife Institute, Bats and Wind Energy Cooperative, National Wind Coordinating Collaborative, and the Utility Variable-Generation Integration Group are working to address wind-related issues ranging from permitting and environmental oversight to manufacturing, workforce training, and facilitation of electric power system integration. These organizations have furthered scientific understanding to help stakeholders realize the role and impact of wind on the energy market, communities, and the environment. Work by collaborative groups has shifted from the basic sharing of information and best practices to active engagement aimed at solving specific problems.

8. Curtailment refers to wind energy available but not used due to transmission constraints and/or system inflexibility.

2.1 Wind Power Markets and Economics

Wind was first used to generate electricity in Scotland in 1887 and was introduced in the United States in 1888 [12]. It was not until nearly a century later, however, that technological research and development—spurred in part by the oil crisis of the 1970s—led to the installation of significant amounts of utility-scale wind power globally and in the United States. From the mid-1980s to the late 1990s, wind began gaining traction in the electric sector.

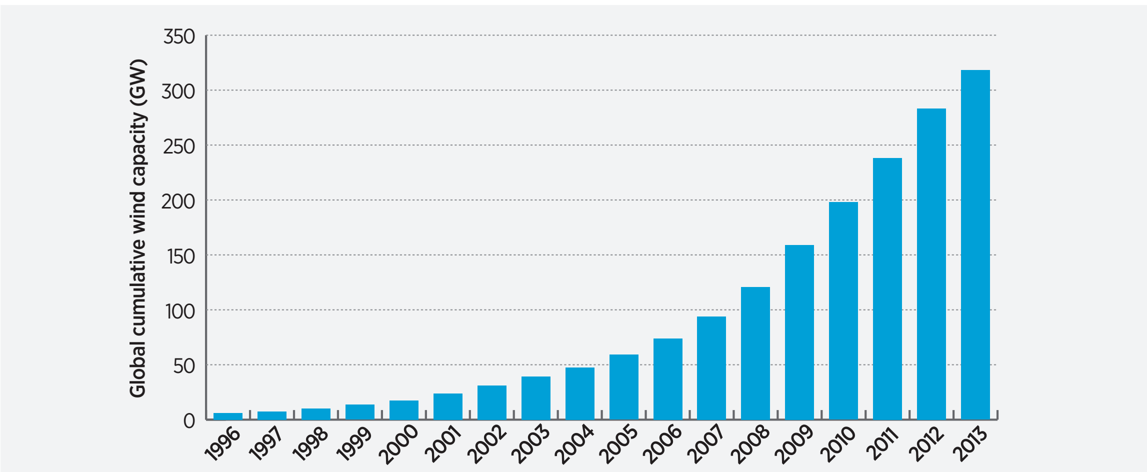
Wind power is cost effective and reliable. Wind power capacity, generation, and investment have grown dramatically.

This section provides insight into various topics related to the wind market. Current global market trends and domestic market trends are summarized in Sections 2.1.1 and 2.1.2. Domestic cost and pricing trends, including cost of energy, PPAs, capital cost, O&M costs, project financing, and project performance are discussed in Section 2.1.3. Section 2.1.4 summarizes U.S. electricity supply and demand issues, including electricity load, natural gas prices, and power plant retirements. Section 2.1.5 discusses market drivers and policy, and covers such topics as federal and state policy for wind, policy uncertainty, and incremental growth trends.

2.1.1 Global Market Trends

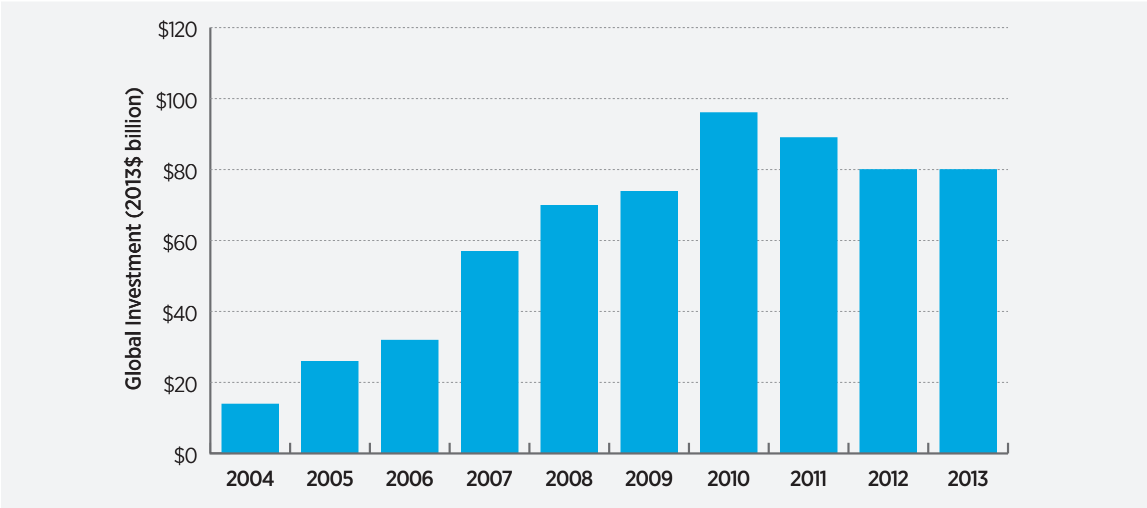
Globally, wind power capacity, generation, and investment have grown dramatically since the late 1990s. Cumulative global installed wind power capacity grew from just 6 GW at the end of 1996 to 318 GW at the end of 2013 (Figure 2-1) [13]. Approximately 3% of global electricity supply came from wind in 2013 [6, 14], up from 0.9% in 2007 [15]. As part of this total, global offshore wind capacity has grown from less than 100 MW in 2000 to nearly 7 GW at the end of 2013 [14]. This capacity is installed mainly in Europe, with a small amount installed in Asia.

According to the United Nations Environment Programme, global investment in wind power grew from $14 billion in 2004 to $80 billion in 2013, a compound annual growth rate of 21% (Figure 2-2) [4, 5]. Wind power represented more than one-third of the total $214 billion invested globally in renewable energy in 2013. Annual investment in wind reached a record high in 2010 at $96 billion, and dropped from 2011 to 2013 due in part to global economic trends as well as falling wind project capital costs. Total wind investment over the decade 2004–2013 was more than $600 billion. An estimated 834,000 global direct and indirect jobs were tied to wind power in 2013 [16].



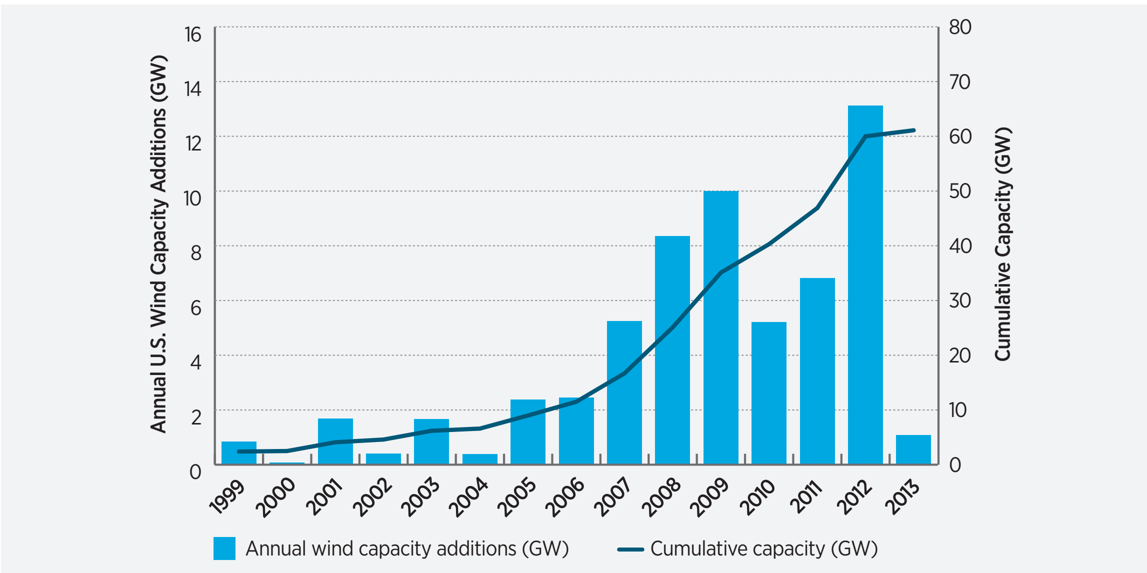
Source: Adapted from the GWEC [13]

Figure 2-1. Global cumulative installed wind capacity, 1996–2013



Source: Adapted from UNEP [5]

Figure 2-2. Global trends in wind power investment, 2004–2013



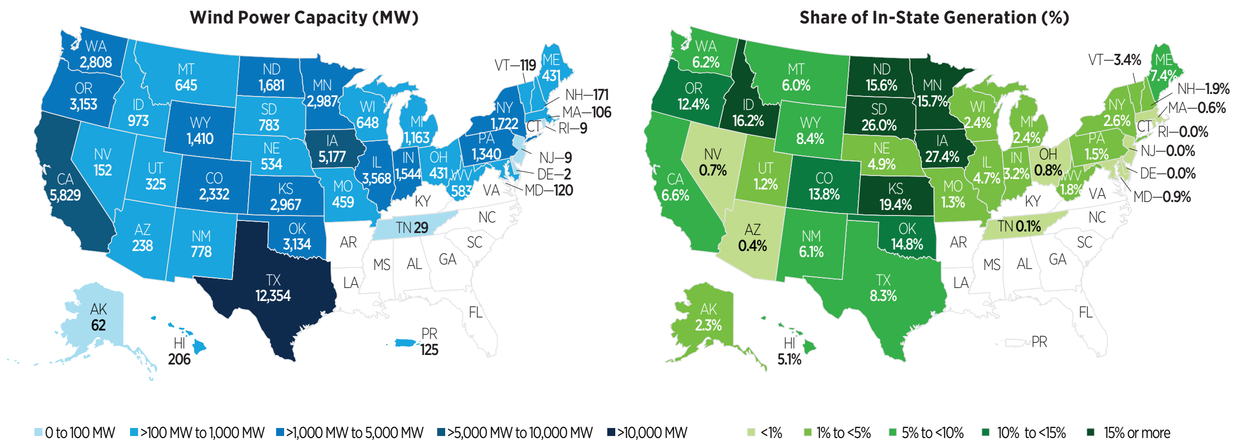
Source: Adapted from AWEA 2014 [7]

Figure 2-3. U.S. installed wind capacity, 1999–2013

2.1.2 Domestic Market Trends

Wind power is an important contributor to domestic power generation in the United States, with cumulative installed wind capacity growing from 1.4 GW in 1996 to 61 GW in 2013 (Figure 2-3) [7, 17]. The *output of electricity* from this wind capacity grew from 3.2 terawatt-hours to 168 terawatt-hours over the same period. This output was equal to 4.5% of national end-use demand (for electricity) in 2013—enough to power 15.5 million U.S. residences [3, 17].

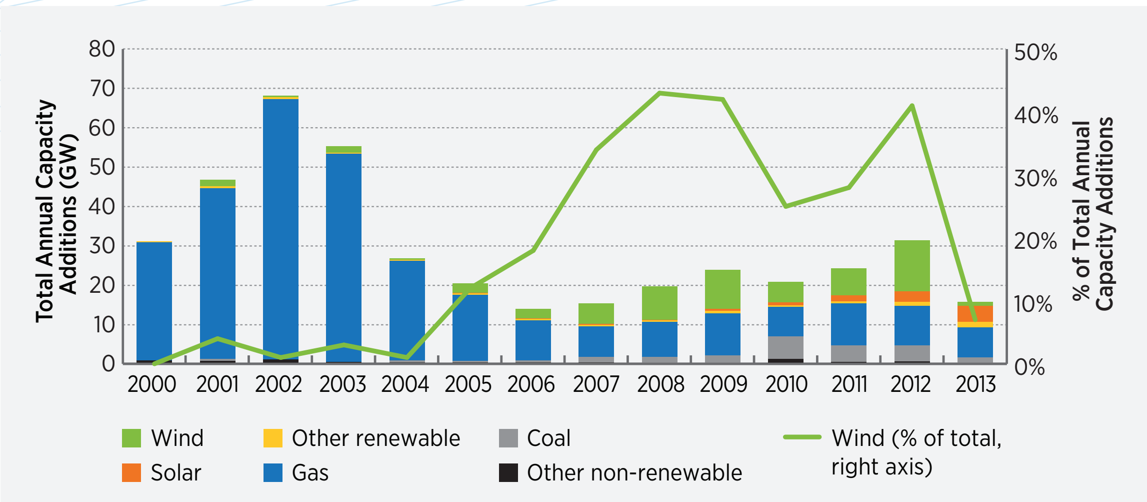
The geographic spread of wind project development in the United States is broad (Figure 2-4). In 2013, nine U.S. states generated more than 12% of their in-state electricity from wind. The top producers were Iowa at 27.4% and South Dakota at 26% [7].



Source: AWEA [7]

Figure 2-4. U.S. utility-scale wind power capacity and share of in-state generation, year-end 2013

Wind power constituted an average of 34% of the total new generating capacity added in the United States each year from 2007 to 2013 [6] (Figure 2-5). The 13 GW of wind installed in 2012 surpassed natural gas to comprise the greatest annual addition of any technology in that year [6]. Wind capacity additions dropped 92% in 2013, however, with only 1.1 GW added representing just 7% of total generating capacity additions [7]. Two key factors contributed to the meager growth in 2013. The first was record growth in 2012 as developers focused on completing projects in advance of the then-planned expiration of federal tax incentives for wind. The second was limited motivation to achieve commercial operations by year-end 2013. This was the result of altered tax incentive eligibility guidelines that, after federal tax incentives were extended, only required construction to have begun by the end of the year. Wind capacity additions in 2013 represented less than $2 billion of investment, down from $25 billion in 2012 [6]. Construction started on a significant number of wind projects in 2013, as developers sought to take advantage of federal tax incentives for projects that initiated construction by year-end. Those projects will come online in 2014 and 2015.



Source: Wiser and Bolinger [6]

Figure 2-5. Relative contribution of generation types in U.S. capacity additions, 2000–2013

Text Box 2-1.

Domestic Market Trends

When *20% Wind Energy* by 2030 was published in 2008, numerous Fortune 100 companies had begun purchasing renewable energy certificates to fulfill corporate sustainability goals concerning energy and greenhouse gas emissions. Renewable energy certificates provide firms the environmental attributes associated with renewable energy without physically changing the firm's electricity supply or providers. Since 2008, corporate purchasing interest has expanded beyond renewable energy certificates into direct power purchase agreements and even on-site direct investment in wind power, indicating long-term corporate commitment to renewable power. By 2012, 59% of Fortune 100 firms had GHG emission reduction commitments, renewable energy commitments, or both [19].

Some recent examples of corporate investment in wind power are noted below:

- By year end 2014, Google had signed 1,040 megawatts (MW) worth of long-term wind contracts, including several 20-year power purchase agreements contracts. These power purchase agreements will power their Iowa, Texas and Oklahoma data centers [20]. Another notable corporate power purchase agreements purchase included Microsoft's agreement to purchase all the electricity from a 175 MW wind plant to supply their Illinois data center [7].
- IKEA Group purchased 2 U.S. wind plants in 2014 [21a, 21b], which together will supply IKEA nearly 1,000 GWh/year of wind energy. IKEA is a full owner of these assets, with Apex Clean Energy operating the plants.
- In 2014, Intel Corporation, Staples, and Unilever were supplied 100% by green power through a combination of solar, wind, and biomass technologies. All three firms fulfilled their renewables portfolio through a mix of on-site generation, renewable energy certificates, and power purchase agreements [20].
- Wal-Mart has a goal of operating with 100% renewable energy by 2020 through a mix of PPAs, on-site generation, and renewable energy certificates. In 2012 Wal-Mart installed its first onsite utility-scale wind turbine at a California distribution center. Wal-Mart also has small wind turbines operating at a Massachusetts store as well as numerous facilities with roof-top solar.

Despite tepid growth in 2013, annual and cumulative wind power installations in the United States have exceeded the early-year pathway (through 2013) in DOE's *20% Wind Energy by 2030* report [18]. This demonstrates that wind can deploy rapidly, as is consistent with high penetration scenarios.

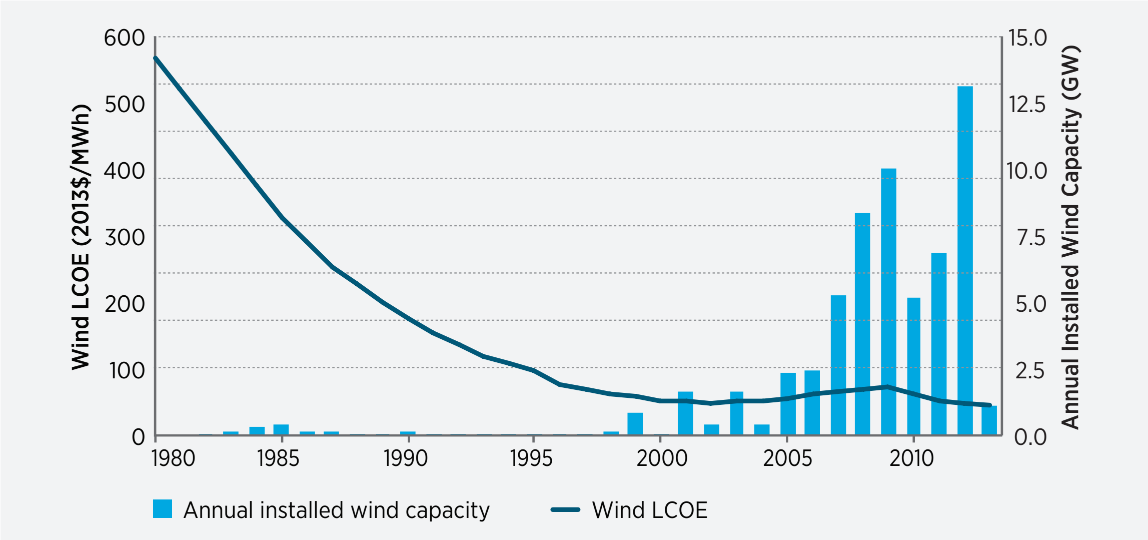
2.1.3 Domestic Cost and Pricing Trends

In sites with higher wind speeds, the LCOE of wind dropped by more than one-third over the five-year period from 2009 to 2013 [6]. In some regional wind markets,[9] wind is competitive with traditional fossil generation [6]. Trends in the cost of wind power and the related prices negotiated in PPAs impact wind power deployment. The LCOE of wind, in turn, is influenced by trends in wind project capital costs; ongoing O&M costs; project financing terms; and project performance.

Cost of Energy

Through technology advancement and turbine scale-up, the average LCOE for U.S. land-based wind projects in good to excellent sites dropped more than 90% from 1980 to 2013—that is, from more than $0.50/kilowatt-hour (kWh) in 1980 to just $0.045/kWh in 2013, excluding the federal production tax

9. The strength of a regional market is determined by a combination of factors, including the natural wind resources, access to transmission, policy incentives and regulatory conditions, and the region's level of historical experience in wind power.



Note: In the *Wind Vision,* 'good to excellent sites' are those with average wind speeds of 7.5 meters per second (m/s) or higher at hub height. LCOE estimates exclude the PTC.

Source: Adapted from Lawrence Berkeley National Laboratory 2014 data [23]

Figure 2-6. Average LCOE in good to excellent wind sites

credit (PTC) [6] (Figure 2-6). Significant variations exist in the LCOE of individual wind projects, however, and projects in lower wind resource sites have higher LCOE. On average, after experiencing an increase beginning in 2003 and peaking in 2009, the LCOE of wind in good to excellent sites[10] dropped by more than one-third over the five-year period from 2008 to 2013. These cost reductions were supported by many factors, including technology advancement, turbine scale-up, and efficiencies gained from larger volume manufacturing.

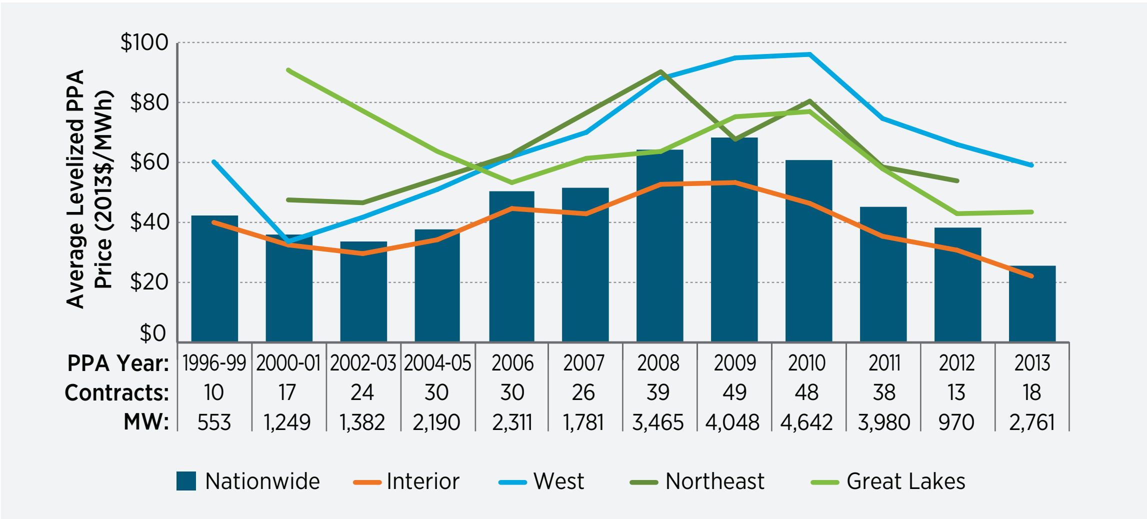
Power Purchase Agreements

Wind PPA prices represent the cost paid by electric utilities for wind power under long-term contracts. Such prices are impacted by the LCOE of wind projects as well as the available federal and state incentives. Average land-based wind PPA prices for a sample of national and regional U.S. wind projects are shown in Figure 2-7. As a result of trends in LCOE and support via federal tax incentives, wind power is now cost-effective in many regions of the United States despite historically low wholesale power prices.

Despite increasing from 2003 to 2009 (Figure 2-7), average wind PPA prices remained competitive with rising wholesale power prices over much of this period [6]. This alignment helped support dramatic growth in wind power additions. Declining wholesale power prices since 2008 have challenged wind economics, but a simultaneous reduction in wind PPA pricing has kept wind competitive in some regions, especially the U.S. Interior [6]. In part as a result of the decline in wind PPA pricing, in 2012 more than 11 GW of wind power capacity was installed in states without any near-term incremental demand from state renewable portfolio standards (RPSs) [22]. In 2013, the national average PPA price for contracts signed was approximately \$25/megawatt-hour (MWh) including the PTC, which is a \$15/MWh reduction from the 2012 generation weighted average [24]. The Interior region of the United States has the lowest PPA prices, largely because it has the best wind resources in the nation.[11] While the wind resource quality in other regions is not expected to change with time, cost improvements gained from wind power experience and advancements in infrastructure, siting, and permitting may help lower PPA prices in these regions in the future.

10. Defined here to include wind projects built in the interior of the country, where some of the nation's most consistent wind resources exist.

11 High quality wind resources are characterized by consistent, predictable high wind speeds.



Note: The Interior region includes Minnesota, Iowa, Missouri, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Montana, Wyoming, Colorado, and New Mexico. The West region includes Washington, Oregon, Idaho, California, Nevada, Utah, and Arizona. The Northeast region includes Maine, Vermont, New Hampshire, Connecticut, New York, Massachusetts, Rhode Island, Pennsylvania, and New Jersey. The Great Lakes region includes Ohio, Indiana, Illinois, Michigan, and Wisconsin.

Source: Wiser and Bolinger [6]

Figure 2-7. Generation-weighted average, levelized wind PPA prices by PPA execution date and region

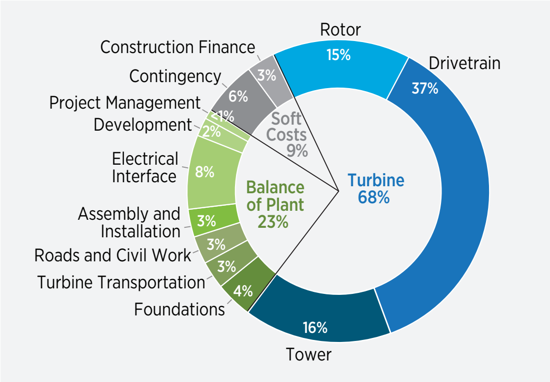
Capital Cost

The capital cost of land-based wind projects has affected trends in wind power LCOE and PPA pricing. Average *wind turbine* prices reached a low of roughly $750/kilowatt (kW) between 2000 and 2002, but then increased between 2004 and 2009 to roughly $1,500/kW—a trend attributed to weakness in the U.S. dollar; rising labor costs, profit margins, and warranty provisions among turbine manufacturers; and increasing raw materials and energy prices [25, 26]. A subsequent reversal of some of these underlying trends, as well as increased competition among manufacturers, led to a significant decrease in turbine prices since 2009. For the most recent (as of 2013) contracts, Bloomberg reports global average pricing of approximately $1,000/kW for older turbine models and $1,300/kW for newer turbine models that feature larger rotors [27].

Total installed *project* capital costs include not only the turbine, but also the balance of system (BOS) costs. BOS costs comprise balance of plant[12] and "soft" costs[13] [28] (Figure 2-8). As shown in Figure 2-9, installed project costs dropped from roughly $5,000/kW in the early 1980s to a low of approximately $1,300/kW in 2004. Similar to turbine costs, project capital costs then increased through 2009 before dropping again. In 2013, the average installed project cost was roughly $1,630/kW, down more than $300/kW from the reported average cost in 2012 and more than $600/kW less than the apparent peak in average reported costs in 2009 and 2010 [6]. With just 11 projects totaling 650 MW, however, the 2013 sample size is limited, which may mean a few large and low-cost projects are unduly influencing the weighted average. Early indications from a larger sample of projects under construction in 2014 (16 projects totaling more than 2 GW) suggest that average installed costs are closer to $1,750/kW—still down significantly from 2012 levels [6].

12. Balance of plant refers to infrastructure elements of a wind plant other than the turbines, e.g., substation hardware, cabling, wiring, access roads, and crane pads.

13. Soft costs are non-infrastructure costs associated with a wind plant, e.g., project development and permitting.



Source: Tegen et al. [28]

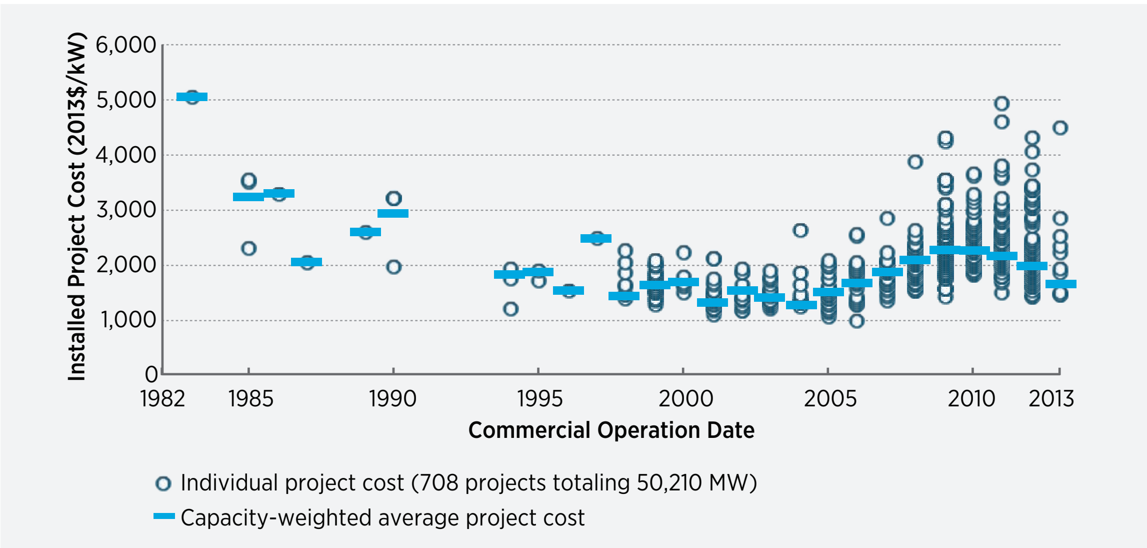
Figure 2-8. Components of installed capital cost for a land-based, utility-scale reference wind turbine

O&M Costs

O&M costs are an important component of the overall cost of wind power and can vary substantially among projects. Anecdotal evidence and analysis suggest that unscheduled maintenance and premature component failure in particular challenge the wind power industry [29]. While O&M cost allocation and categorization is not consistent across the industry, a recent report found U.S. wind O&M costs comprise scheduled maintenance (20.5%), unscheduled maintenance (47.7%), and balance of system (31.9%) [30].

Though market data on actual project-level O&M costs are not widely available, some overall cost trends can be discerned. First, as noted, O&M costs generally increase as projects age [25]. Second, trends by project vintage are unclear, with some analysis suggesting increasing costs in recent years (to 2014) and other analysis suggesting the opposite [25, 29, 31].

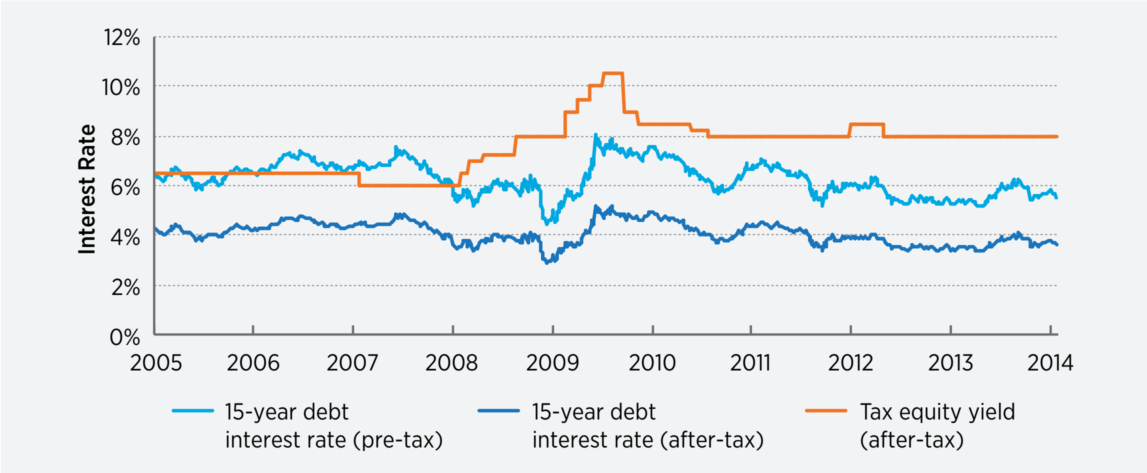
Aside from the lack of clarity in underlying O&M cost trends, however, inspection and monitoring programs have generally improved over time to focus on preventive maintenance for gearboxes, generators, blades, and related equipment. These programs combine information from condition monitoring systems,[14] supervisory control and data acquisition (known as SCADA), asset management software, and increased technical experience to identify trends and proactively ensure wind power plants run at high availability at the lowest possible costs. Turbine manufacturers are also now signing full-service O&M contracts lasting up to 20 years, compared to historical O&M contracts of just two to five years. This indicates increasing confidence in wind technology reliability and the ability to generate revenue by operating wind plants.



Source: Wiser and Bolinger 2014 [6]

Figure 2-9. Installed wind power project costs over time

14. Condition monitoring systems use sensors that measure key operating characteristics of gearboxes, generators, blades, and related equipment to alert operators when non-standard operating conditions occur. Condition monitoring systems are a major component of predictive maintenance.



Source: Wiser and Bolinger 2014 [6]

Figure 2-10. Cost of 15-year debt and tax equity for utility-scale wind projects over time

Project Financing

Wind power is capital intensive, which makes costs for wind highly sensitive to the cost of capital. In the United States, the weighted average cost of capital available to wind project sponsors is artificially inflated by the fact that federal incentives for wind power development are delivered through the tax code (see Section 2.1.2). Most wind project sponsors do not have sufficient "tax liability" to fully benefit from these federal tax incentives, and so they need to rely on third-party tax equity investors to monetize them. This third-party tax equity, however, is a relatively more expensive source of capital. As shown in Figure 2-10, tax equity is currently more than twice as expensive (on an after-tax basis) as the term debt that would likely replace it if monetization were not necessary.[15]

Even the minority of project sponsors that are able to take the tax credits directly on their own (and so do not need to partner with tax equity investors) will often end up with a suboptimal capital structure because they cannot borrow as effectively against PTCs as against cash revenue. Collectively, these impacts of tax incentives on capital structure and cost suggest that altering how federal incentives for wind power deployment are delivered could significantly reduce the cost of capital available to wind project sponsors, allowing wind PPA prices and the LCOE to decline commensurately [32].

Project Performance

Since the early 2000s, turbine manufacturers have developed turbines featuring larger rotors and higher hub heights capable of economically generating power at lower wind speed sites (average wind speeds of less than 7.5 m/s) (see Section 2.5). These substantial advances have had the effect of increasing project performance and opening lower wind speed areas of the country for possible land-based wind development [33, 25, 24, 34]. Since 2012, these larger-rotor turbines have been increasingly deployed in higher wind speed locations (where average wind speeds are more than 7.5 m/s), leading to anticipated wind project capacity factors that sometimes exceed 50%. This is well above what was common through 2014 [35, 24].[16] See Section 2.5 for more details about the effects of technology advancement on annual energy capture and LCOE.

15. The returns of equity investors in renewable energy projects are most 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 first 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%.

16. Capacity factor is a measure of the productivity of a power plant, calculated as the amount of energy that the plant produces over a set time period (typically a year) divided by the amount of energy that would have been produced if the plant had been running at full capacity during that same time interval.

As previously mentioned, turbine manufacturers now sign full-service O&M contracts lasting up to 20 years, demonstrating increased confidence in wind technology and revenue potential.

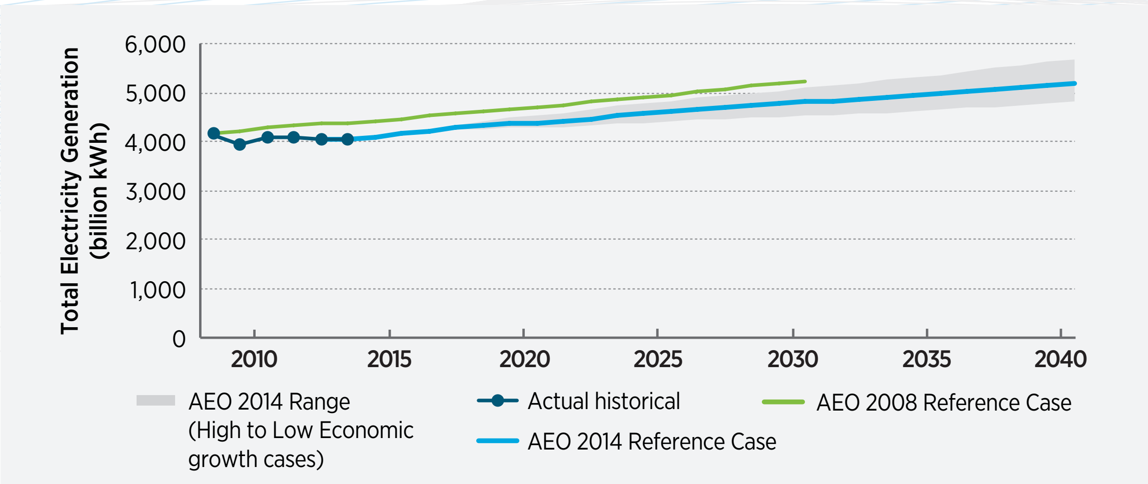
2.1.4 U.S. Electricity Supply and Demand

Wind power deployment is impacted by broader trends in the energy market, including electricity load, the price of other energy sources, and electric power plant retirements. As other forms of electricity generation face regulatory and market challenges, wind power has become a cost effective source of energy, in part due to its declining costs. Despite flat electricity demand and declining natural gas prices, wind deployment has still increased.

Electricity Load

Low electricity load growth since 2008 has reduced the need for new electricity generation. As shown in Figure 2-11, the actual amount of electricity generation required to meet load since 2008 has been largely flat. This generation has also been far lower than what the EIA predicted in its Annual Energy Outlook (AEO) in 2008,[17] though some increase in load was experienced between 2012 and 2013. These lower levels of electricity demand have created a more challenging economic environment for wind; without as much need for new supply, new wind projects need to compete to a greater extent with existing—rather than new—forms of generation.

Electricity supply is projected to grow an average of 0.9% per year through 2040, a minimal change from the 1% per year that was predicted in 2008 [36, 37]. Flat load growth since 2008 means that even the "high economic growth" projection from the AEO 2013 [37] falls below the AEO 2008 reference case projection [36]. While the exact load growth is uncertain, lower levels of projected electricity demand are expected to continue to create a challenging economic environment for wind. If load growth exceeds expectations, however, wind deployment could increase more than anticipated. One study, for example, estimated that transportation electrification could generate nearly 500 billion kWh of new annual demand by 2050, or almost 13% of 2013 U.S. net electric power sector generation [3, 38].

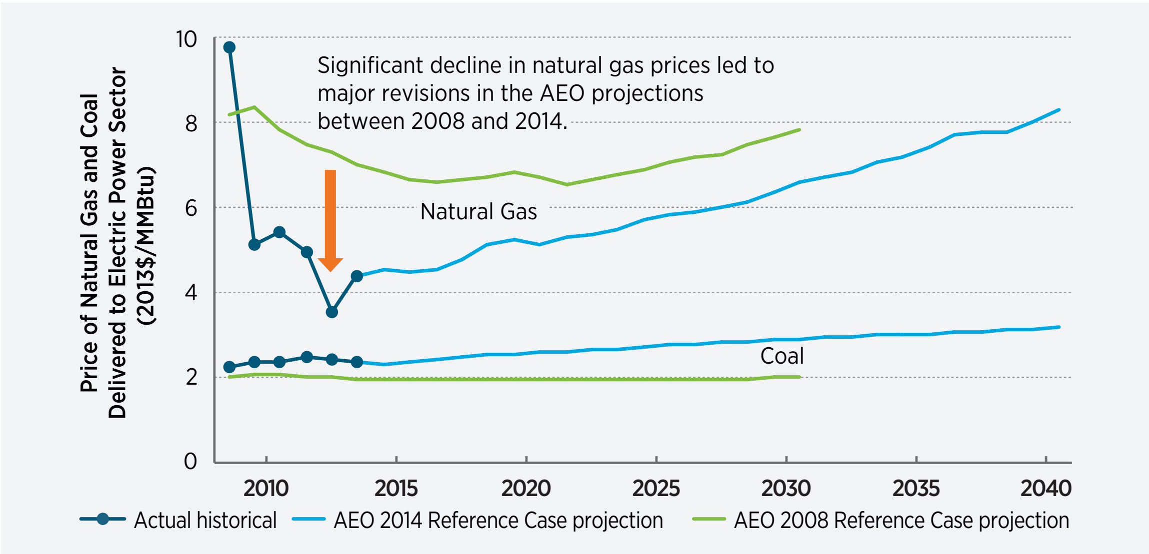


Note: EIA publishes the *Annual Energy Outlook* to project energy and fuel costs. The Reference Case is the main 'central' estimate reported. There are several additional cases that project energy demand and costs under a variety of economic and fuel cost conditions. The range illustrated above depends on a range of economic growth assumptions.

Source: EIA [42]

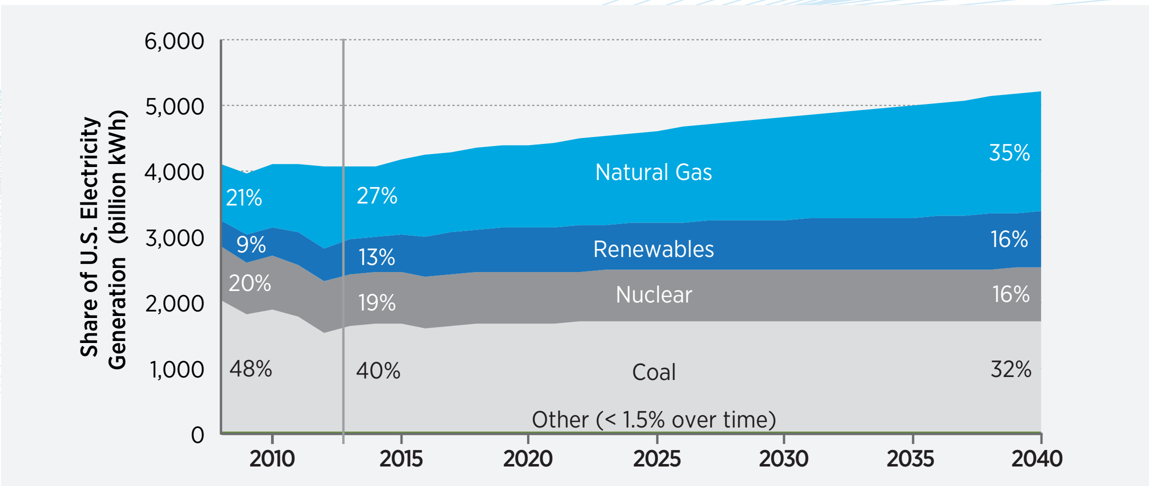
Figure 2-11. AEO projected load growth cases vs. actual

17. The DOE Energy Information Administration produces an Annual Energy Outlook, which defines a "reference case" and specifies "high" and "low" ranges of projected electricity generation for analytical purposes, The AEO is available at: *http://www.eia.gov/forecasts/aeo/*.



Source: EIA [42]

Figure 2-12. Natural gas and coal prices and projections from two AEO Reference Cases



Source: EIA [42]

Figure 2-13. Historical and projected U.S. electricity generation by fuel in AEO Reference Case 2014

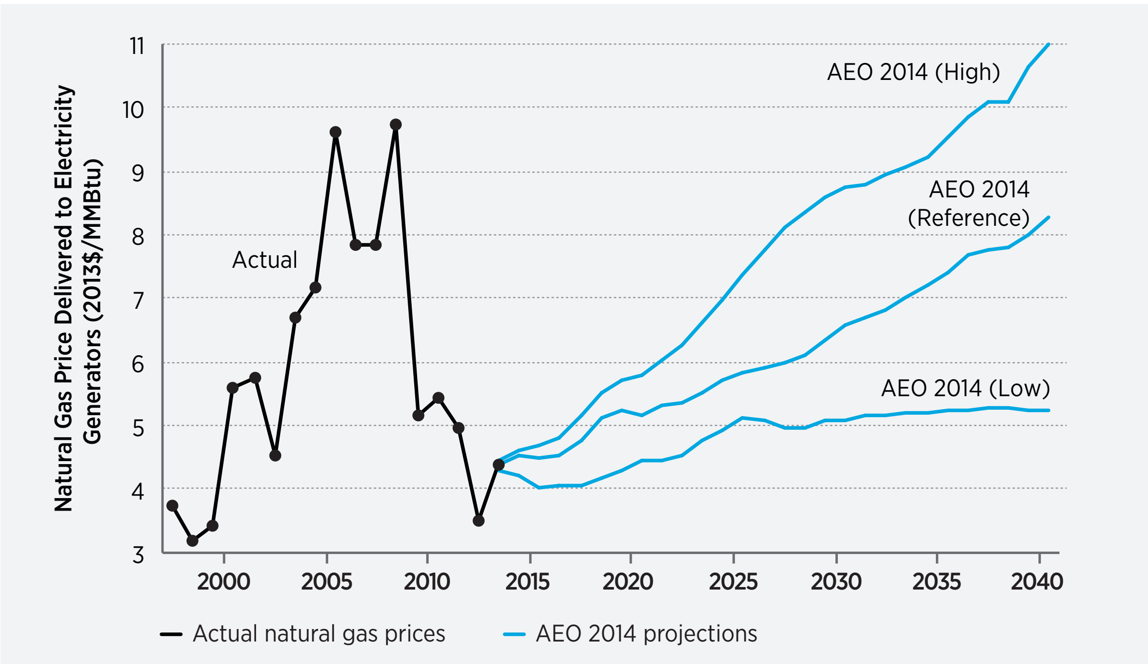
Natural Gas Prices

Since 2008, the increase in natural gas reserves enabled by advances in horizontal drilling and hydraulic fracturing has been among the more important energy supply-side developments impacting wind power [39, 40]. In response to this new supply (along with tepid demand from a sluggish economy), natural gas prices have fallen dramatically from their peak in mid-2008 (Figure 2-12), prompting a considerable amount of fuel-switching in the power sector (Figure 2-13). The share of natural gas-fired generation in the U.S. power mix increased from 21% in 2008 to 27% in 2013 [41], while coal-fired generation declined from 48% to 37% over this same period. Though coal prices have remained relatively steady, these developments with natural gas have pushed wholesale power prices down from the highs seen in 2008 (Figure 2-12), resulting in increased competitive pressures for wind power.

The future generation mix, especially the share of natural gas-fired generators, will affect the market competitiveness of wind power (Figure 2-13). Although natural gas prices (and price projections) remain below 2008 levels, prices have already recovered somewhat from lows seen in 2012. Natural gas prices are projected to increase further through at least 2040, as demand increases due to anticipated economic growth and opportunities to export natural gas or use it for transport (Figure 2-14).

Increased use of natural gas for electricity offers positive effects for wind generation because gas's price elasticity makes wind more competitive. Greater numbers of natural gas power plants, however, have the potential to create competition for wind. Because natural gas power plants can vary their generation output more quickly than coal or nuclear plants, they offer utilities greater flexibility to respond to changes in wind power output.

As of 2013, low natural gas prices and expectations about future price make it more difficult for wind to compete on economic grounds [43]. Still, it is important to recognize that natural gas prices have historically been unpredictable. The 2013 EIA AEO [37] projected a wide range of prices between the low, reference, and high gas price cases, from less than $5.50/million British thermal units, or MMBtu, to greater than $10.50/MMBtu in 2040 (Figure 2-14). This price uncertainty stems from unclear demand, lack of clarity on the future amount of liquefied natural gas exports, public concerns about hydraulic fracturing, and uncertainty about the size of the domestic natural gas resource base [43]. The potential negative impact of gas price uncertainty and volatility on consumer costs is exacerbated by the challenge of effectively hedging gas prices over longer terms [43]. While these factors also lead to uncertainty about the future competitiveness of wind vs. gas—and, therefore, future wind deployment—they also highlight the possible role that wind might play as a hedge against some of these risks. This topic is explored further in Section 2.4.6 and in Chapter 3.



Note: EIA publishes the *Annual Energy Outlook* to project energy and fuel costs. The Reference Case is the main 'central' estimate reported. The High and Low projections of this figure refer to AEO's Low Oil and Gas Resource and High Oil and Gas Resource Cases, respectively.

Source: Lawrence Berkeley National Laboratory compilation of forecasts and data from EIA

Figure 2-14. Actual natural gas prices and AEO forecasts

Table 2-1. EPA Rules under Development in 2014 Affecting Power Plants

Rule	Goal	Initially Planned Effective Year	Status (2014)
Cross States Air Pollution Rule	Limit air pollution transport	2012	Upheld by Supreme Court in April 2014
Mercury and Air Toxins	Limit mercury and other hazardous gases	2015	Upheld by Appeals Court in April 2014
Coal Combustion Residual	Manage safe disposal of coal ash	Pending final rule	Near final, but the rule could take two different routes
Cooling Water Intake Structures § 316(b)	Protect fish and aquatic life	2021	EPA finalized standards in May 2014
Guidelines to Clean Air Act Section 111(d)	Reduce carbon pollution from the power sector	2015	Released draft in June 2014 and a final rule by June 2015

Source: Adapted from information from the U.S. Environmental Protection Agency

Power Plant Retirements

Retirement of conventional power plants will affect the future potential for wind deployment. Retirements of coal and nuclear power plants have already occurred as a result of competition with lower-cost natural gas plants. In locations in which wind power can compete economically with natural gas, that conventional generation can be replaced with wind power. Environmental regulations will also influence decisions about power plant technologies. As of early 2014, new EPA rules about environmental concerns other than GHGs were in varying stages of development and implementation (Table 2-1). Additional policies potentially affecting wind deployment are discussed in Section 2.1.5.

Two GHG-specific rules are also under development by the EPA for new and existing power plants as of 2014. The first rule, which has been released in proposed form, could prevent construction of new coal plants unless they integrate carbon capture and sequestration technology [44]. The second rule, focused on existing plants and released in draft form in 2014, could result in additional retirement of fossil generators.

Proposed changes to the Clean Air Act Section 111(d) were introduced in 2014 as well (Table 2-1). In this action, the EPA proposed state-specific, rate-based goals for CO_2 emissions from the power sector, as well as guidelines for states to follow in developing plans to achieve the state-specific goals. This rule would continue progress already underway to reduce CO_2 emissions from existing fossil fuel-fired power plants in the United States.

Numerous studies have analyzed which power plants would likely be impacted from investment in new technologies to comply with the possible forthcoming rules, and which would be more advantageous to retire [40]. Many of these studies estimate that these rules could lead to an increased cost of fossil fuel-fired generation and the retirement of 45–70 GW of coal plants by 2020. For example, an August 2013 survey indicates that, since 2006, 58 GW of coal plants have announced retirements by 2025 [45]. Coal plant retirements are projected to be greater if proposed GHG rules are also considered.

Nuclear plant retirements are anticipated in part due to lower natural gas prices. The catastrophic failure of Japan's Fukushima I Nuclear Power Plant has also increased scrutiny of nuclear safety. A 2013 study found that up to 38 nuclear reactors are "at risk" of retiring early [46]. Announcements had been made by the end of 2013 to close several nuclear plants, including San Onofre, California; Crystal River, Florida; Kewaunee, Wisconsin; and Vermont Yankee, Vermont.

2.1.5 Market Drivers and Policy

Rising wholesale electricity prices and growth of renewable energy incentives, helped facilitate the expansion of wind power. Policy uncertainty, low natural gas prices, modest electricity demand growth, and limited additional demand from state RPS policies will continue to affect the wind industry. Cycles of wind deployment have been created by short-term extensions and periodic expirations of federal tax incentives. This fluctuating market creates challenges for wind developers, manufacturers, transmission planners, utility purchasers, and other stakeholders.

Federal and State Policy for Wind

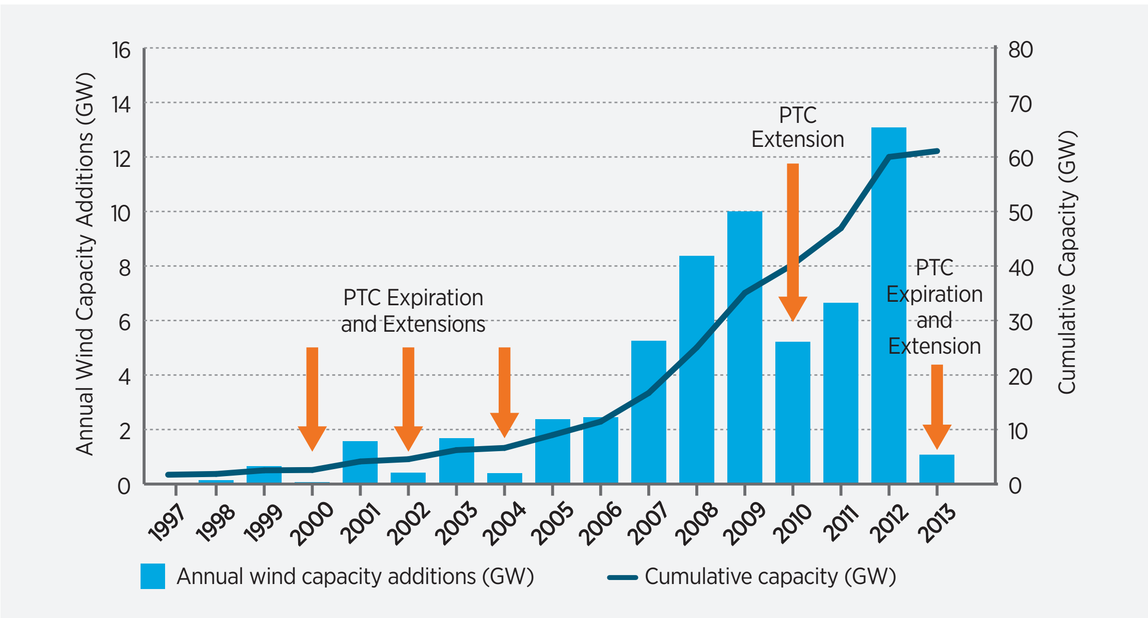
Various federal and state policies have underpinned the domestic wind power market since the industry's beginnings in the 1980s [47]. The most influential federal policy is the PTC as first enacted through the Energy Policy Act of 1992, H.R.776. Later provisions included the investment tax credit (ITC) and a provision under the American Recovery and Reinvestment Act of 2009—known as the Recovery Act—that enabled wind power projects to elect, for a limited time, a 30% cash grant in lieu of the PTC or ITC [25].[18]

As of 2013, 29 states plus Washington, D.C., had mandatory RPS programs. Though direct correlations between RPSs and the amount of wind development are not clear [48, 49, 50, 51], and RPSs are not the only driver of development, 69% of wind power capacity added in the United States from 1999 through 2013 was located in states with RPS policies. Beyond RPSs, state policies that have supported growth of the wind industry include utility resource planning efforts, state renewable energy funds, voluntary "green power" programs, various forms of state tax incentives, and state and regional carbon-reduction policies [25].

Policy Uncertainty and Incremental Growth Trends

Federal and state policies have been integral to the success of the wind industry.

As shown in Figure 2-15, wind deployment has dropped significantly each of the four times the PTC



On January 1, 2014, the PTC expired again and lapsed for more than 11 months. In early December 2014, the PTC was extended again, but was valid only through year-end 2014.

Sources: American Wind Energy Association

Figure 2-15. Historical wind deployment variability and the PTC

18. The Database of State Incentives for Renewable Energy provides additional information on state and federal renewable energy policies at *www.dsireusa.org*, as does the United States Department of Agriculture Rural Development Energy Programs website, *http://www.rd.usda.gov/programs-services/rural-economic-development-loan-grant-program*.

Text Box 2-2.

Key Federal Policies Affecting Wind Power

PTC and ITC: Originally enacted in the Energy Policy Act of 1992, the PTC is a production-based tax credit available to various renewable energy sources. The PTC provided a 2.3¢/kWh tax credit for the first 10 years of electricity generation for utility-scale wind. The ITC (available as of 2013) provides a credit for 30% of investment costs and is especially significant for the offshore and distributed wind sectors because such projects are more capital-intensive than land-based. In January 2013, the PTC and ITC were extended through the American Taxpayer Relief Act. Wind power projects larger than 100 kW can qualify for the PTC or ITC if construction was started before January 1, 2014 (turbines under 100 kW are eligible until 2016), by satisfying the "program of continuous construction" and "continuous efforts," and being placed into service by the end of 2015.

Recovery Act: The American Recovery and Reinvestment Act of 2009 (Pub.L. 111–5), known as ARRA or the Recovery Act, allowed wind projects to take the ITC in lieu of the PTC. ARRA also created the Section 1603 Treasury grant, a temporary program that enabled specified energy property built by the end of 2012—including wind projects—to receive a cash grant of 30% of a project's capital costs in lieu of either the PTC or ITC. Given the challenges in securing tax equity during the financial crisis, Section 1603 has been credited with supporting the continued growth of the renewable energy sector during what otherwise was a challenging investment environment. The program also reduced barriers for newer and less-experienced wind developers, who might otherwise have faced sizable challenges in accessing the limited supply of tax equity. The proportion of wind power additions supported by the grant include 44% of new wind capacity installed in 2012, 62% in 2011, 82% in 2010, and 66% in 2009. ARRA also created the Section 1705 loan guarantee program for commercial projects, which closed on four loan guarantees to wind projects totaling more than 1,000 MW.

Accelerated Depreciation: Accelerated depreciation through the federal Modified Accelerated Cost-Recovery System, known as MACRS, allows wind project owners to depreciate most project capital costs on a five-year schedule. The Economic Stimulus Act of 2008 (Pub.L. 110–185, 122 Stat. 613) and subsequent legislation provided a further 50% first-year bonus depreciation provision for projects built between 2008 and 2010. The American Taxpayer Relief Act of 2012 (Pub.L. 112–240, H.R. 8, 126 Stat. 2313), extended a 50%, first-year bonus depreciation to projects placed in service through December 31, 2013.

has expired, as well as during the economic downturn and during the onset of increased shale gas availability around 2009–2010. Wind has also experienced *increased* development in years in which incentives are otherwise scheduled to expire by year-end, as projects rush to meet tax incentive eligibility rules. The "boom-and-bust" cycle created by short-term extensions and periodic expirations of federal tax incentives has created challenges for wind developers, manufacturers, transmission planners, utility purchasers, and other stakeholders [52].

At the state level, many RPS policies are close to being fully met. As a result, the incremental demand for renewable energy under these existing programs is somewhat limited. Lawrence Berkeley National Laboratory (LBNL) projects 3–4 GW/year of new renewable energy through 2025 [6]. Bloomberg projects that 2 GW/year may come from wind, whereas the American Wind Energy Association (AWEA) forecasts roughly 2.4 GW/year of wind from 2013–2025 [53]. These figures are well below annual wind power capacity additions as of 2013. The nature, design, and stringency of future policy drivers that might affect wind installations are uncertain.

2.1.6 Conclusions

Global wind power capacity, generation, and investment have grown dramatically since the late 1990s, and wind power is an important contributor to domestic power generation in the United States. The LCOE of wind in good to excellent wind resource sites dropped by more than one-third over the five-year period from 2009 to 2013 [6], and, in some of the strongest wind markets, wind is competitive with traditional fossil generation [6]. Trends in the cost of wind power and the related prices negotiated in PPAs impact wind power deployment. The LCOE of wind, in turn, is influenced by trends in wind project capital costs; ongoing O&M costs; project financing terms; and project performance.

Wind power deployment is impacted by broader trends in the energy market, including electricity demand, the price of other energy sources, and electric power plant retirements. As other forms of electricity generation face regulatory and market challenges, wind power has become a cost effective source of energy, in part due to its declining costs. Despite flat electricity demand and declining natural gas prices, wind deployment has still increased.

The wind industry is also affected by policy uncertainty. Wind deployment cycles have been demonstrably influenced by extensions and periodic expirations of federal tax incentives. This cyclical behavior creates challenges for wind developers, manufacturers, transmission planners, utility purchasers, and other stakeholders. Section 4.9 of the *Wind Vision* roadmap discusses three key areas in which the wind stakeholder community can collaborate with others to maintain the analysis capability necessary to inform policy decision makers, including: comprehensively evaluating the costs, benefits and impacts of energy technologies; refining and applying policy analysis methods; and tracking technology advancement and deployment progress and updating the roadmap.

2.2 Offshore Wind

Global offshore wind deployment offers extensive experience from which the United States can learn—at the close of 2013, a total of 2,080 wind turbines were installed and connected to the electricity grid, in 69 offshore wind plants in 11 countries across Europe. Total installed capacity of these turbines reached nearly 6.6 GW at the end of 2013, producing 24 terawatt-hours (TWh) in a normal wind year, enough to cover 0.7% of the European Union's total electricity consumption. The European Wind Energy Association identified 22 GW of consented[19] offshore wind plants in Europe as of 2013, and plans for offshore wind plants totaling more than 133 GW [2]. Worldwide, more than 200 GW of offshore wind were in the regulatory pipeline at the end of 2012 according to assessments by the National Renewable Energy Laboratory (NREL) [54].

Section 2.2.1 discusses trends in the U.S. offshore industry, while Section 2.2.2 examines current offshore costs. Section 2.2.3 reviews the deployment and siting issues affecting the U.S. offshore industry.

2.2.1 Status of the Offshore Industry

Offshore turbines can be located near load centers with some of the highest electric rates in the United States and provide an alternative to long distance transmission of land-based wind power from the Interior to the coasts. The North Atlantic, South Atlantic, Great Lakes, Gulf of Mexico, and West Coast all contain significant offshore wind resources, and projects have been proposed in each of these areas. Environmental organizations in the United States are helping to educate interested parties and are supporting the development of offshore wind. In 2012, the National Wildlife Federation authored, "The Turning Point for Atlantic Offshore Wind Energy," which

Deployment experience in Europe shows that offshore wind is technologically viable. In the United States, offshore is poised for an industry launch.

19. The European Wind Energy Association classifies projects as online, under construction, or consented.

advocates offshore wind development off the Atlantic Coast. The report was endorsed by 40 other environmental organizations [55].

Universities are also leading research on offshore wind. In June 2013, the University of Maine's DeepCwind Consortium launched VolturnUS off the coast of Castine, Maine. VolturnUS comprises a one-eighth scale semi-submersible floating foundation—the first offshore wind turbine deployed in the United States. A number of full-scale projects are also under development within the domestic offshore market. In 2014, Navigant identified 14 offshore wind projects totaling 4,900 MW that had reached an "advanced stage of development [56]."[20] Developer timelines indicate the first of these projects may come online in 2015.

The federal government, including the DOE and the U.S. Department of the Interior (DOI), has also stepped up efforts to accelerate the development of offshore wind. In February 2011, DOE initiated the Offshore Wind Strategic Initiative and launched more than $250 million in public/private research and development funding grants and cooperative agreements. The capstone of this effort is a plan to deploy three Advanced Technology Demonstration projects by 2017. The three finalists for the deployment are Dominion Power (Virginia), Fishermen's Energy (New Jersey), and Principle Power Inc. (Oregon). The federal regulatory process for offshore wind, led by the Bureau of Ocean Energy Management (BOEM), has also evolved considerably since 2008. Following the issuance of the first commercial lease to Cape Wind in 2010, BOEM held successful auctions for three lease areas: off the coasts of Rhode Island/Massachusetts and Virginia in 2013, and off the coast of Maryland in 2014. State regulatory processes in the Great Lakes have also advanced, with issued leases for offshore wind projects in state waters totaling more than 1.2 GW [57].

Despite this progress and the fact that the U.S. offshore wind industry will be able to draw on more than 20 years[21] of international experience with the technology,[22] offshore wind faces several challenges in the United States. Foremost among these concerns is the high cost of offshore wind technology, combined with uncertain policy support [57].

2.2.2 Offshore Costs

Given that no offshore wind projects exist in the United States as of 2014, the costs of such projects is generally uncertain. Some indication about the likely costs of offshore projects can be derived, however, from global experience. During the period 2004–2012, capital costs for offshore wind projects increased as the industry came to terms with the true costs and risks of developing projects in technically challenging offshore sites. Navigant indicates that the average reported cost of offshore wind projects installed globally in 2012 was $5,385/kW[23] [57]. This cost roughly represents a doubling of costs from those observed in the 2002-2007 time period. This increasing cost trend was a result of numerous factors, including:

- A shift toward developing projects in sites characterized by greater water depths, longer distances to shore, and more intense meteorological and ocean conditions;
- A greater understanding of the risks associated with offshore construction, which has resulted in increased spending on risk mitigation as well as higher contingency budgets; and
- A lack of competition in the supply chain—particularly for offshore wind turbines, with 82% of turbines installed in 2012 sold by a single manufacturer [57, 59].

20. *An advanced stage of development* for an offshore wind project is defined as having achieved at least one of the following three milestones: (1) received approval for an interim limited lease or a commercial lease; (2) conducted baseline or geophysical studies at the proposed site with a meteorological tower erected and collecting data, boreholes drilled, or geological and geophysical data acquisition system in use; and/or (3) signed a PPA with a power off-taker [57].

21. The world's first offshore wind park began operation in 1991 in Vindeby, Denmark [58].

22. At the end of 2013, GWEC estimated an installed capacity of approximately 7 GW. The vast majority of this capacity (over 90%) is located in northwestern Europe, where 10 countries have installed offshore wind projects. The remaining capacity is located in Asia, where Chinese, Japanese and South Korean markets show signs of accelerating activity [13].

23. Financial results reported in the 2013 "Offshore Wind Market and Economic Analysis: Annual Market Assessment" Navigant report are in 2011$.

Notwithstanding this trend, data on the near-term project pipeline[24] suggest capital costs appear to be stabilizing. In projects installed in 2013 for which data are available, the average reported capital cost was $5,187/kW, compared to $5,385/kW for projects completed in 2012[25] [56]. While it appears that the stabilizing trend may continue for projects completed in 2014, a lack of data for projects anticipated to reach completion in 2015 and 2016 makes it difficult to assess whether the trend will continue [56].

In the United States, four offshore wind PPAs have been approved to date.[26] All four were motivated at least in part by state policies to encourage utility demand for offshore wind power. The effective bundled prices of these PPAs range from approximately $180/MWh to $240/MWh in 2012 dollars, with terms extending between 15 and 25 years [60]. These PPAs give some indication of domestic offshore wind power prices. Future project and turbine scale increases combined with new technology may further reduce market prices.

The relatively high LCOE for initial offshore wind projects, combined with generally low natural gas prices, means that offshore projects will need stable and long-term policy support. RPSs that reach 30% in the densely populated Northeast will require consideration of offshore wind due to limited space to develop land-based wind and solar at sufficient scale. To facilitate public utility commission approvals allowing utilities to pass the costs of these early offshore wind projects to ratepayers, state legislatures have amended relevant statutes to enable consideration of a range of environmental and economic benefits from the contracts beyond just LCOE (see Chapter 3). Examples include Massachusetts,[27] Rhode Island,[28] and Maryland [57].[29]

It is unlikely that offshore wind projects in the United States will be self-financed. Offshore developers will instead likely seek commercial project financing based on the strength of the market and finance mechanisms, as well as other project contracts and the credit of the power purchaser and other project counterparties. For example, Cape Wind, which has secured long-term PPAs from National Grid and NSTAR, has engaged the Bank of Tokyo-Mitsubishi UFJ, Natixis, and Rabobank [61] as lead arrangers of its debt financing who have committed more than $400 million. For example, Cape Wind secured long-term PPAs and arranged debt financing in 2014 [61, 62, 63]. Wind turbine vendor Siemens has offered to secure financing for the project as needed [63].

2.2.3 Offshore Deployment and Siting

Offshore wind is still in early development phases, but significant progress is being made to facilitate siting, leasing, and construction of offshore wind power projects in both federal and state waters. The main siting concerns focus primarily on questions of competing use, environmental impacts, and constraints due to the availability of technology to meet some challenging design conditions (e.g., water depth issues). Other issues include the timelines and investment required to develop new port facilities, heavy-lift construction vessels, and supply chains for major components. Additional concerns over coastal viewshed issues, understanding of offshore wind resources, and grid interconnection and integration issues also require further investigation.

24. Near-term pipeline includes projects that are either under construction or have signed major supply contracts as of mid-2014.

25. Financial results reported in the 2014 "Offshore Wind Market and Economic Analysis: Annual Market Assessment" Navigant report are in 2012$.

26. These include: a PPA between NRG Bluewater and Delmarva (canceled by NRG Bluewater in December 2011) enabled by legislation that increased the value of renewable energy credits (RECs) generated by the project to 350% of normal levels, and PPAs between Deepwater Wind and National Grid, Cape Wind and National Grid, and between Cape Wind and NSTAR, all driven by state government interventions that allow the utility to pass through the above-market prices of the contracts, as well as a rate of return, to its customers.

27. The peak demand price suppression benefits of the Cape Wind PPA was cited by both the Massachusetts Department of Public Utilities and the Massachusetts state supreme court when approving the PPA. Alliance to Protect Nantucket Sound v. Department of Public Utilities, 461 Mass. at 176–177, September 8, 2011.

28. Public Law 2010, Chapter 32, amending Title 39 Section 26.1.

29. Maryland enacted legislation in 2013 establishing Offshore Wind Renewable Energy Certificates as a financial support mechanism for offshore wind projects that are approved by the public utility commission, after review of several factors, including reductions of locational marginal pricing, transmission congestion, capacity prices, and other net economic, environmental and public health benefits to the state." (Maryland Code - Public Utilities Article, 7–704.1(D)).

The rapidly evolving federal regulatory process and new state-based policies (in some areas) are supportive of future offshore wind developments in federally designated offshore wind energy areas (WEAs) (Text Box 2-3).

Figure 2-16 identifies the current location and approximate size of the proposed WEAs and other wind development zones that have been proposed, leased, or are under development in state and federal waters. While there has been activity in both state and federal waters, meeting the penetration levels of the *Wind Vision Study Scenario* for offshore wind would require large-scale development under federal jurisdiction on the Outer Continental Shelf (OCS). BOEM is the lead agency charged with leasing offshore wind sites in federal waters on the OCS. The Bureau of Safety and Environmental Enforcement, BOEM's sister agency, is charged with ensuring safe operation of offshore wind on the OCS but has had only a small role as of 2013 because there are no operational U.S. offshore wind projects. Several other federal agencies, including the National Oceanic and Atmospheric Administration (NOAA) and the Army Corps of Engineers, play significant roles in the permitting process. These agencies provide oversight and concurrence to BOEM under its leasing process and, in some cases, are required to issue their own permits.

In 2007, BOEM prepared a programmatic environmental impact statement covering much of the Atlantic coast to support the future regulatory process for leasing offshore wind turbines in the area. BOEM has also developed a series of guidance documents for developers on providing information (e.g., avian surveys, spatial data, and benthic surveys) to support offshore renewable energy permitting. The guidance documents are available on BOEM's website (*www.boem.gov/National-and-Regional-Guidelines-for-Renewable-Energy-Activities/)*. In April 2009, BOEM released the primary regulations that provide the framework for offshore renewable energy projects

Text Box 2-3.

Offshore Wind Energy Areas (WEAs)

- BOEM, which controls rights to submerged federal lands, has initiated the "Smart from the Start" program, which aims to facilitate rapid and responsible development of the offshore wind resource [64].
- BOEM has been working with industry, state policymakers, other regulatory agencies, and stakeholder groups to identify priority WEAs on the Atlantic outer continental shelf.
- BOEM has conducted Environmental Assessments in several WEAs and published "Findings of No Significant Impact," which cleared the way for the commercial leasing process and site assessment activities.
- The first leases for development rights within the Rhode Island/Massachusetts WEA and the Virginia WEA have been competitively auctioned. Together these leases grant development rights to more than 270,000 acres of submerged land, which could support up to 5 GW of offshore wind capacity.
- These lease sales, with a total up-front volume of $5.4 million (and additional payments as and if development proceeds), demonstrate the commercial interest in developing offshore wind projects [65, 66].

on the OCS [67].[30] In 2010, DOI initiated a "Smart from the Start" program for siting and leasing offshore wind projects within designated WEAs on the Atlantic coast [68]. Under this framework, BOEM has initiated a process to designate offshore WEAs in close coordination with federal and state regulators, state interagency task forces, and other stakeholders [64]. The WEAs are developed under a broad marine spatial planning process and vetted to minimize conflicts with wildlife and human uses. This effort is conducted in partnership with adjacent states, federal authorities, and major stakeholders.

As part of the analysis of impacts from proposed offshore wind construction, operation, and decommissioning, BOEM considers existing and likely future uses of the coastal and ocean environment and develops best management practices (BMPs) to address potential navigation effects of offshore wind projects. This includes siting of wind plants to avoid unreasonable interference with major ports and Traffic Separation Schemes designated by the U.S. Coast Guard, as well as placing proper lighting and signage on structures to aid navigation and comply with applicable Coast Guard regulations. One example of work to support this is a study published by BOEM to address fishing industry concerns about potential displacement and disruption by offshore wind plant siting. The goal of the study was to work in close consultation with representatives from the fishing industry and wind power developers to develop agreed-upon best management practices and mitigation measures. These best management practices and mitigation tools can be used to develop offset scenarios to support siting analysis and decision making under the National Environmental Policy Act and other applicable statutes. These best management practices will also be used to foster compatible use areas of the OCS and reduce conflicts within portions of the U.S. Atlantic OCS that might be used simultaneously by the wind power industry and fishermen [69]. Results of the study are discussed in the report, "Development of Mitigation Measures to Address Potential Conflicts between Commercial Wind Energy Lessees/Grantees and Commercial Fishers on the Atlantic Outer Continental Shelf."[31]

A primary concern of NOAA's National Marine Fisheries Service is the potential impact on the endangered North Atlantic right whale from survey and construction noise and potential vessel collisions. Several offshore wind developers and environmental organizations reached an agreement on protective mitigation measures such as restrictions on vessel activities during certain periods of whale migration and the use of trained independent observers on survey and construction vessels in the Mid-Atlantic.[32] This agreement was facilitated under guidance and standards set by BOEM.

BOEM will subdivide the larger WEAs into smaller developable leasing areas and auction them off individually to offshore wind developers [70, 71, 72, 73]. This approach addresses requirements for a fair competitive process and results in exclusive site control for the successful bidders. The first two competitively auctioned commercial leases have been awarded through this process, off the coasts of Massachusetts and Rhode Island, and off the coast of Virginia [74, 75]. An additional lease sale occurred in Maryland in 2014. Other lease sales are expected in Massachusetts and New Jersey during 2015.

Some of the wind development zones shown in Figure 2-16 (non-WEAs) were submitted to BOEM as unsolicited lease applications. In these cases, BOEM is required to determine whether there is competitive interest before issuing an exclusive lease. If a competitive interest exists, BOEM holds a lease auction. If no competitive interest exists, BOEM can proceed with the leasing process under a bilateral negotiation with the applicant.

30. The Minerals Management Service was the precursor agency to BOEM and the Bureau of Safety and Environmental Enforcement and was originally designated as the lead agency to support offshore wind development under the Energy Policy Act of 2005.

31. Report is available at *http://www.boem.gov/Draft-Report-on-Fishing-Best-Management-Practices-and-Mitigation-Measures/*.

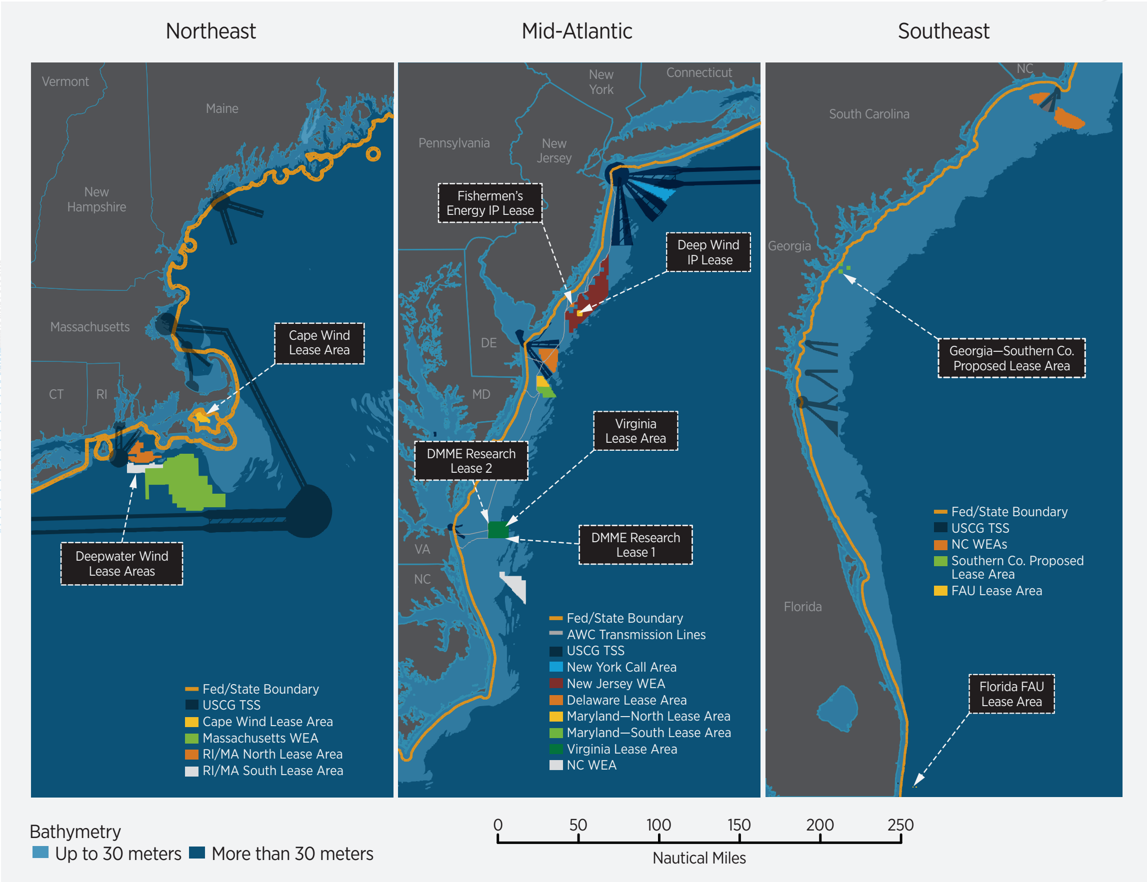
32. "Proposed Mitigation Measures to Protect North Atlantic Right Whales from Site Assessment and Characterization Activities of Offshore Wind power Development in the Mid-Atlantic Wind Energy Areas," letter to BOEM from Deepwater Wind and other developers and Natural Resources Defense Council and other organizations, December 12, 2012.

Examples of unsolicited proposals include:

- Cape Wind, which was granted the first commercial offshore lease in the United States in October 2010 [76][33] before the BOEM review process existed;
- Virginia Offshore Wind Technology Advancement Project- a project conducted by Dominion Power that received a finding of no competitive interest for a research lease to the Virginia Department of Mines, Minerals, and Energy [74]; and
- A 30-MW commercial lease application in Oregon by Principle Power Inc., which received a finding of no competitive interest [69].

Applications also include non-wind projects such as the Atlantic Wind Connection shown in Figure 2-16. This project proposes the installation of a 6 GW offshore grid backbone that could facilitate the distribution of power from North Carolina to New York, but does not include any specific offshore wind power plants.

A few offshore wind projects have been proposed and permitted in state waters (within three nautical miles from the coast in most cases). In addition, many states on the Atlantic coast have proactively established site selection and marine spatial planning processes for state waters that have designated areas for offshore wind development, and have implemented



Note: Bathymetry is the study of underwater depth of lake or ocean floors. Acronyms used in graphic: U.S. Coast Guard (USCG); Coast Guard Traffic Separation Schemes (TSS); Wind Energy Area (WEA); Interim Policy (IP); Virginia Department of Mines, Minerals, and Energy (DMME); Atlantic Wind Connection (AWC); Florida Atlantic University (FAU).

Source: National Renewable Energy Laboratory

Figure 2-16. BOEM-defined wind energy areas for the Eastern seaboard as of November 2013

33. The lease to Cape Wind preceded the current regulations by several years and was granted under a special structure which provided not only site control but was approved as a specific project. This differs significantly from lease practices as of 2013, which only provide site control and initiate the opportunity to study the site and design a project.

project review and permitting processes supporting development. The waters of the Great Lakes are also under state jurisdiction. All offshore wind projects are subject to some level of state permitting due to the need for transmission cables to shore and interconnection with the grid. With so few permitted offshore projects in the United States, however, the regulatory process for offshore wind is largely untested. State agencies lead permitting efforts in state waters, including federal consistency through the Coastal Zone Management Act and state-delegated authority for water quality permits under the Clean Water Act, plus, typically, wetlands approval and a submerged lands lease. Offshore wind plants in state waters also have to comply with all applicable federal regulations.

2.2.4 Conclusions

Deployment experience in Europe confirms that offshore wind is technologically viable. In the United States, offshore projects have been proposed in areas with significant offshore wind resources. Although significant progress is being made to define siting, leasing, and construction procedures for offshore wind power projects, work remains to achieve broader deployment potential for offshore. Some vital steps include continued LCOE reductions and technology advancements, such as floating turbine structures; policy creation and stabilization; decreased regulatory timelines and complexity; development of local supply chains; and enhanced installation logistics capabilities.

The *Wind Vision* roadmap (Chapter 4) discusses actions related to development of a U.S. offshore industry. Section 4.1 discusses the need to collect and analyze data to characterize offshore wind resources and the external design conditions for all coastal regions of the United States. This section of the roadmap also discusses the need to validate forecasting and design tools at heights at which offshore turbines operate. Section 4.2 includes discussion of the need to develop next-generation wind plant technology for rotors, controls, drive trains, towers, and offshore foundations for continued improvements in wind plant performance. The development of an offshore wind manufacturing and supply chain, an important element to offshore wind's contribution to the *Wind Vision Study Scenario*, is discussed in Section 4.3. Section 4.5 reviews the need to develop optimized subsea grid delivery systems and evaluate the integration of offshore wind under multiple arrangements to increase utility confidence in offshore wind, while Section 4.6 discusses the need to develop clear, consistent, and streamlined regulatory guidelines for wind development.

2.3 Distributed Wind

Distributed wind power systems offer reliable electricity generation in a wide variety of settings, including households, schools, farms and ranches, businesses, towns, communities, and remote locations. Distributed wind projects are connected on the customer side of the meter (either physically or virtually[34]) to offset all or a portion of the energy consumption at or near the location of the project, or directly to the local grid to support grid operations. This model differs from the centralized power plant distribution model used by land-based wind plants and offshore wind applications. This section discusses the trends of the U.S. distributed wind industry, including market growth, as well as deployment and siting issues facing the industry.

Distributed wind projects are in all 50 states, Puerto Rico, the Commonwealth of Northern Marianas, and the U.S. Virgin Islands. Distributed wind systems often compete with retail electricity rates and have the potential to become more competitive.

Distributed wind systems are used by households, schools, industrial facilities, institutions, municipalities, and other energy consumers. These systems are particularly appropriate in remote or rural locations in which people need or want to produce part or all of their electricity needs. Primarily installed where people

34. Virtually connected distributed wind projects are projects where credits for wind generation not directly connected to the load are applied to customers' bills through remote net metering or meter aggregation. Aggregated, remote, or group net metering authorizes participants to jointly benefit from a single net metered renewable system that is not directly connected to each customer's meter.

live and work, distributed wind projects often serve as "ambassadors" of wind power in that they can often be the public's first exposure to wind turbines.

Because distributed wind is classified based on a wind project's location relative to end-use and power distribution infrastructure, rather than on technology size or project size, the technologies and system sizes can vary significantly. Distributed wind can include small systems of less than 100 kW up to utility-scale turbines of 1 MW and more.

Given the broad applicability of distributed wind project applications, such projects exist in all 50 U.S. states, Puerto Rico, the Commonwealth of Northern Marianas, and the U.S. Virgin Islands. This widespread use of distributed wind is significant because some states in the southeastern United States do not have large wind plants, but they all have some type of distributed wind project.

The primary decision-making authorities for distributed wind project permitting are local and state governments. While several states may have permitting processes for large-scale, land-based wind plant projects, few address distributed wind at the state level and only a small portion of cities and counties have permitting processes in place for distributed wind projects. This lack of established standards and familiarity with distributed wind on the part of authorities can create an inefficient and costly project development process for installers and developers who need to navigate through state, local, and utility regulations (or lack thereof), while educating officials along the way. In a step to alleviate this, the Distributed Wind Energy Association (DWEA) published a set of model ordinances and guidelines [77] to lead local governments through adoption of solid and defensible ordinances for turbines used in distributed applications.

The United States is a world leader in the export of small wind turbines (up to 100 kW) used in distributed applications. U.S. small wind turbine manufacturers exported $103 million of small wind turbines in 2013 [78], or nearly a quarter of the value of utility-scale wind exports. Table 2-2 highlights U.S. small wind turbine exports in MWs. The recorded small wind capacity installed worldwide is estimated to be more than 678 MW as of the end of 2012, the last year for which global data are available [79].

Table 2-2. U.S. Small Wind Turbine Manufacturers' Exports and Domestic Sales

Year	Exports (MW)	Domestic Sales (MW)
2006	3	7
2007	4	9
2008	5	13
2009	10	17
2010	8	21
2011	18	15
2012	8	6
2013	14	4

Source: Orrell and Rhoads-Weaver [78]

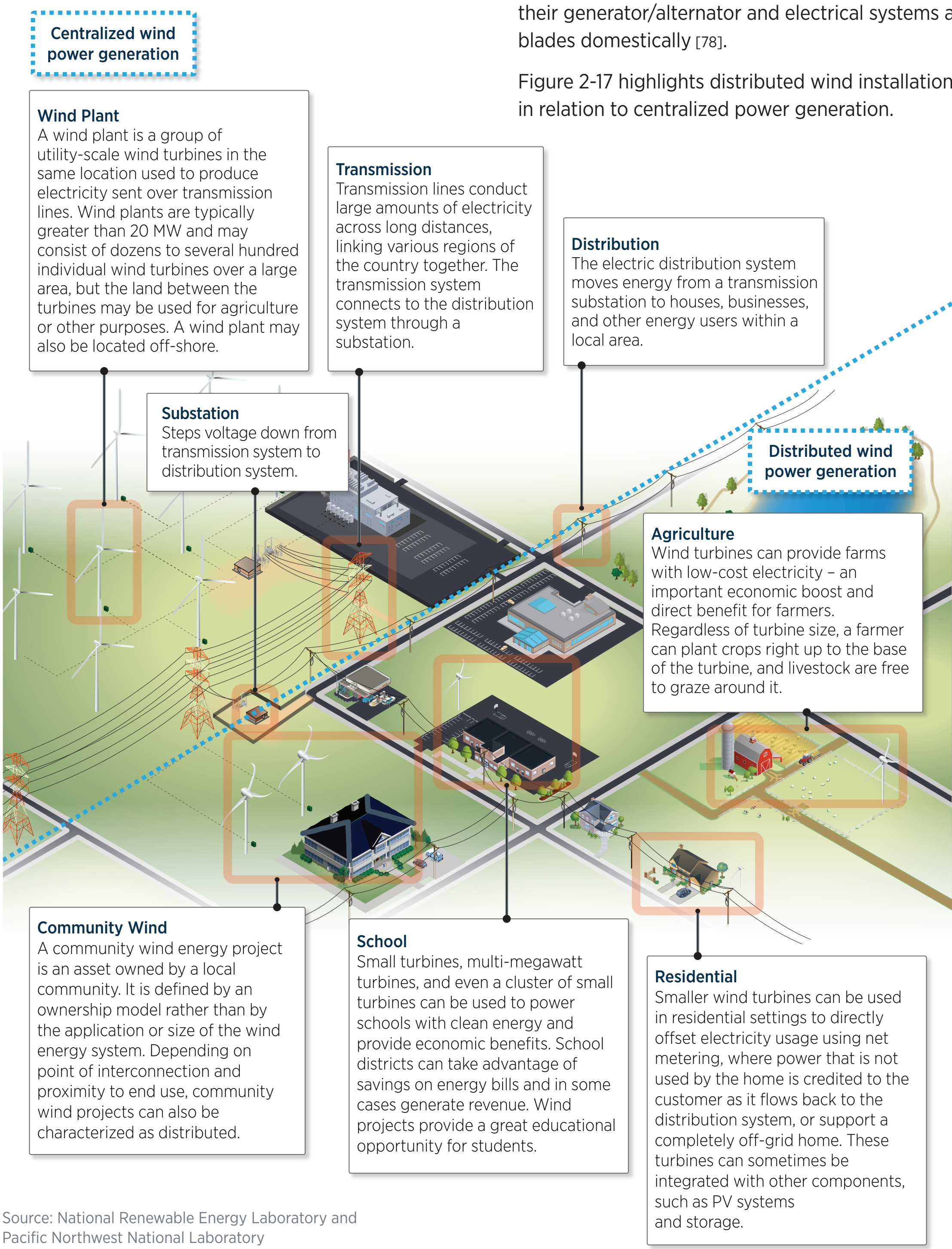
Frameworks and testing facilities have emerged in the United States in recent years to certify small wind turbines to national performance and safety standards, signaling a maturing small wind marketplace. While U.S. manufacturers dominate the small wind turbine market, the distributed wind market depends on imports for turbines larger than 100 kW [80].

Manufacturing facilities for distributed wind systems are widespread. Hundreds of manufacturing facilities and vendors are spread across at least 34 states, comprising:

- at least 31 facilities actively assembling, manufacturing, or refurbishing wind turbines used in distributed applications;
- at least 17 facilities manufacturing wind turbine blades and other composites;
- at least 12 facilities producing wind turbine towers;
- at least 10 facilities producing drive trains and other electrical components;
- dozens manufacturing wind turbine mechanical components; and
- numerous other facilities involved in the manufacturing supply chain (e.g., materials and construction equipment suppliers, financiers, and insurance and other service providers) [78].

Leading U.S.-based small wind turbine manufacturers (i.e., those with large market shares) rely on a largely U.S. supply chain for most of their turbine components, maintaining hardware domestic content levels of 80 to 95% [78]. A total of 13 manufacturers, representing half of 2013 U.S. small wind sales capacity, reported sourcing more than two-thirds of their generator/alternator and electrical systems and blades domestically [78].

Figure 2-17 highlights distributed wind installations in relation to centralized power generation.



Source: National Renewable Energy Laboratory and Pacific Northwest National Laboratory

Figure 2-17. Distributed wind system applications in relation to centralized power generation

Text Box 2-4.

Distributed Wind in Alaska

Alaska, separated from the contiguous United States, is essentially an islanded grid. While dependent on imported resources, such as diesel fuel, Alaska also draws on its own resources to supply its electricity, and wind power is playing a small but increasing role in Alaska's energy generation portfolio. The biggest incentive for wind power development in remote villages of Alaska is the technology's ability to displace the high cost of imported diesel fuel. In the more populated area known as the Railbelt, which includes the city of Anchorage, wind is diversifying the energy mix and providing a hedge against the risk of rising natural gas prices.

While Alaska had 4 MW of installed wind capacity in 2008, it had 59 MW at the end of 2013 [7]. This large increase in installed capacity is mainly the result of multiple projects that went online in 2012, including the 24.6 MW Eva Creek project near Fairbanks and the 17.6 MW Fire Island project in Anchorage (Figure 2-18). The rest of the capacity can be attributed to wind-diesel hybrid systems now operating in more than 20 remote villages. In some cases, these systems provide more than 20% of the village's electrical generation and have made Alaska a world leader in wind-diesel hybrid systems.

Challenges for wind project development in Alaska include the harsh, cold climate; limited human and financial resources; technical challenges associated with integrating wind on small isolated grids; and shipping, construction, and maintenance cost and logistics. Many turbines installed in Alaska have cold weather packages, which may include heating systems for the lubrication system and control cabinets or black blades to reduce ice build-up. In addition, turbines can require special foundation designs to ensure the permafrost ground stays frozen in the summer. Heavy equipment, such as cranes, often can only be mobilized when the permafrost ground is frozen and ice is out of the waterways to allow barge access to deliver equipment and turbine parts. Harsh weather conditions can also delay technicians reaching turbines needing maintenance [81].

Despite these challenges, the citizens of Alaska continue to pursue innovative ways to interconnect more wind power, further reducing the need for high-cost, imported energy resources and increasing the state's energy independence.

Source: Bill Roth/Anchorage Daily News

Figure 2-18. Fire Island 17.6-MW project in Alaska

2.3.1 Conclusions

Distributed wind was a strong growth market from 2008 through 2012, and distributed wind projects are currently in all 50 states, Puerto Rico, the Commonwealth of Northern Marianas, and the U.S. Virgin Islands. Various policy and market conditions—including increased adoption of net metering; increasing retail electricity rates; falling technology costs; and numerous federal, state, and local incentives for distributed generation—could support further growth of distributed wind deployment in the United States. Section 4.5 of the *Wind Vision* roadmap (Wind Electricity Delivery and Integration) discusses the need to improve grid integration of and increase utility confidence in distributed wind systems.

2.4 Economic and Social Impacts of Wind for the Nation

In the United States, wind power is already reducing greenhouse gas emissions as an important part of the electric generation mix. As wind generation displaces generation from carbon-based fuels, harmful emissions and water use by power plants are also reduced. In the process of providing this renewable energy, wind power plants create jobs, a new income source for landowners (lease payments), and tax revenues for local communities in wind development areas. Utilities are using wind to mitigate financial risk within their portfolios with fixed-price contracts of long duration.

Economic benefits of wind power are widespread and include: direct employment, land lease payments, local tax revenue, and lower electricity rates in wind-rich regions. Environmental benefits include substantial reductions in greenhouse gas emissions, air pollutants like oxides of sulfur and nitrogen, and water consumption.

Section 2.4.1 discusses greenhouse gas (GHG) emissions and estimated offsets from wind power. Section 2.4.2 summarizes the economic development impacts of wind power, and workforce development, including job training and workforce safety, is discussed in Section 2.4.3. Air pollution impacts of wind power, water use, and risk and diversity are covered in Sections 2.4.4, 2.4.5, and 2.4.6 respectively.

2.4.1 GHG Emissions

Wind power displaces GHG-emitting generation, which contributes to meeting GHG emission reduction goals. Total energy-related CO_2 emissions in the United States equaled 5.4 billion metric tonnes (5.95 billion short tons) in 2013, of which approximately 35% came from the power sector [82]. Wind power generates no direct emissions, has low life-cycle emissions, and displaces CO_2 and other GHGs that would otherwise be emitted by fossil fuels. Wind power in the United States in 2013 was estimated to have reduced direct power-sector CO_2 emissions by 115 million metric tonnes (127 million short tons), equivalent to eliminating the emissions of 20 million cars during the year [10].

According to the Intergovernmental Panel on Climate Change, the GHG emissions produced in the manufacture, transport, installation, operation, and decommissioning of wind turbines are small compared to the emissions avoided over the lifetime of wind power plants [83, 84]. In addition, the energy consumed for those processes are typically balanced after three to four months of operation at a standard site. Based on an extensive and updated review of studies conducted for the *Wind Vision* impacts analysis (see Chapter 3), the life-cycle GHG emissions of wind are approximately 1% that of subcritical coal, 3% that of combined-cycle natural gas, and comparable to or lower than those of other non-emitting energy sources. Though concerns have been expressed that the variability of wind output (and resultant cycling of fossil plants) might degrade its benefits in reducing GHGs, recent research summarized in Chapter 3 shows that this effect is modest in comparison to wind's emissions reduction benefits[35] [85].

The *20% Wind Energy by 2030* report showed that higher penetrations of wind power could further reduce GHG emissions from the power sector [18], an analysis that is updated and extended in Chapter 3 of the *Wind Vision*. The degree of carbon reduction depends on what power plants are displaced and is regionally dependent [86]. The conclusion that increased wind power reduces GHG emissions, however, has been confirmed by a number of studies conducted by a range of institutions. For example:

- In 2013, the Western Wind and Solar Integration Study showed that achieving 33% wind and solar in the United States portion of the western grid could avoid 29-34% of power-sector CO_2 emissions from the Western grid [87].

35. The incremental fossil plant cycling incurred as a result of meeting 33% of electricity demand in the western United States with wind and solar generation was found to reduce the renewable generation emission reduction benefit by 0.2%.

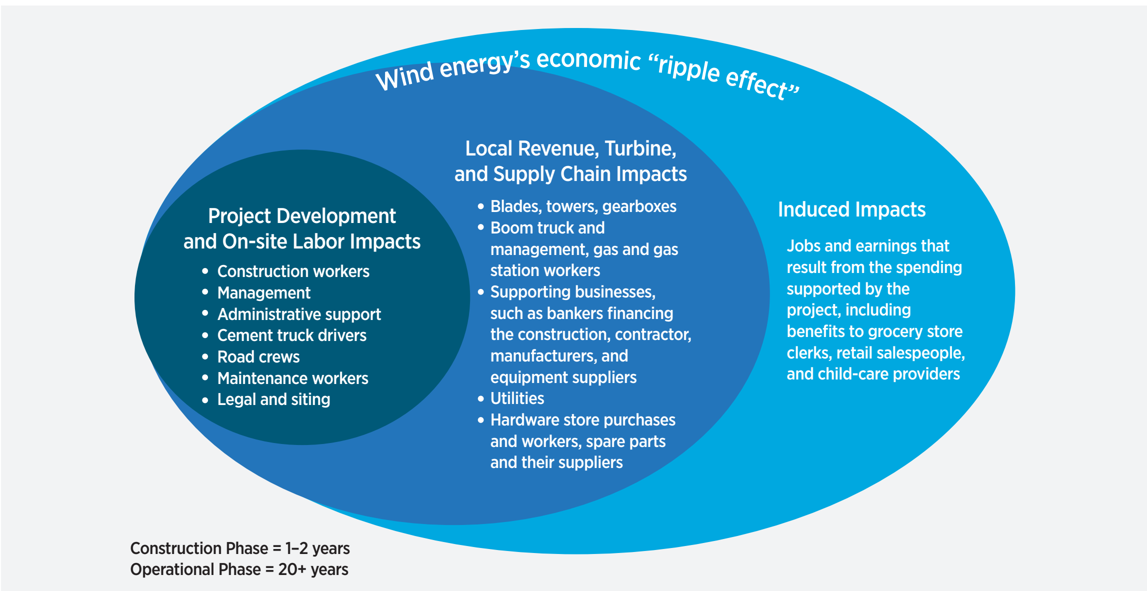
- A 2011 study from Navigant Consulting found that a four-year PTC incentive for wind could spur wind deployment and offset 154.2 million metric tonnes (170 million short tons) of CO_2 from 2011 to 2016 [88].
- Research published in 2014 for the PJM Interconnection power grid operator estimated that 20% wind and solar energy scenarios could reduce the Mid-Atlantic region's power-sector CO_2 emissions by 14-18% vs. a 2% renewables scenario [89].

2.4.2 Economic Development

Wind power development has an economic "ripple effect" for its locality, region, and the nation (Figure 2-19). Wind development and its related manufacturing facilities generate nationwide jobs in sectors such as engineering, construction, transportation, financial, and consultancy services. Future offshore wind installations are expected to open additional opportunities such as repurposing underutilized port infrastructure, employing the maritime trades, and engaging marine science technologies.

Economic development is an important aspect influencing local acceptance of wind power. A 2011 survey conducted in Iowa and west Texas found that more than two-thirds of respondents in several communities near wind plants in the two locations felt their county had benefited economically from wind plants and that the plants were a source of job creation. Support for wind power in these communities was associated with socioeconomic factors rather than foundational aesthetic or moral values; in fact, wind plants were perceived as the vehicle to reverse economic decline [90].

Several national studies have also documented the economic and social impacts of wind development. A 2012 study of 1,009 counties across 12 states with wind development determined that wind power installations between 2000 and 2008 increased county-level personal income by approximately $11,000 and employment of approximately 0.5 jobs for every megawatt (MW) of installed capacity [8]. These estimates translate to a median increase in total county personal income and employment of 0.2% and 0.4% for counties with installed wind power over the same period. A separate study, conducted in 2011, used NREL's Jobs and Economic Development Impacts, model—known as JEDI—to estimate economic impacts from 1,398 MW of wind power development in four rural counties in west Texas. During the four-year construction phase, the study estimated that 4,100 full-time equivalents jobs were supported by this level of capacity. Turbine and supply chain impacts (see Section 2.6) accounted for 58% of all jobs generated. The total economic activity in the local communities was



Source: NREL

Figure 2-19. Economic ripple effects of wind development estimated to be nearly $730 million over the assumed 20-year lifecycle of the plants, or $520,000 (2011$) per MW of installed capacity [91].

A study of the first 1,000 MW of wind power developed in Iowa[36] (between 1999 and 2008) confirmed the following [92] [37]:

- Employment during construction of nearly 2,300 FTE jobs;
- Addition of approximately 270 permanent jobs;
- Total economic activity during construction of nearly $290 million;
- Economic activity during operation of nearly $38 million per year;
- More than $6 million per year generated in property taxes; and
- Nearly $4 million per year provided as lease income to Iowa landowners.

To be clear, these figures focus on gross labor force and economic development impacts related specifically to wind and are not net jobs and economic impacts reported for the state of Iowa.

2.4.3 Workforce

Workforce is a key component of economic development from wind power, and the size of the wind-related workforce has been affected by policy fluctuations that disrupt domestic demand. All 50 states, as well as 71% of the 435 U.S. Congressional districts (held by both parties), had an operating wind project, a wind-related manufacturing facility, or both at the close of 2013 (Figure 2-21) [7]. According to statistics from AWEA, these activities provided jobs in industrial as well as rural areas. Table 2-3 provides a breakdown of wind-related employment in recent years.

New wind projects demand up-front labor for resource assessment, project siting, and permits. In 2012, jobs were lost in the development sector as developers waited for outcomes to uncertainty about the 2013 policy environment and status of the PTC. AWEA reports total jobs linked to the wind industry fell to 50,500 by the close of 2013 [7]. The record installation activity of 2012, however, supported significant increases in construction, transportation, operations, and other project-related jobs, often in rural areas that benefited from the multiplier effects of commercial

Table 2-3. U.S. Employment Linked to Wind Power Development

	2011	2012	2013
Turbine Deployment			
Annual turbine installations	6.8 GW	13.1 GW	1.0 GW
Total turbines operating	38,000	45,000	46,000
Manufacturing			
Manufacturing facilities	470	580	560
Employment			
Total FTE[a] wind jobs	75,000	80,700	50,500
Manufacturing jobs	30,000	25,500	17,400
Construction sector jobs	9,400	16,700	9,600
Wind technician jobs	4,000	7,200	7,300
Other jobs	31,600	31,300	16,200

[a]The American Wind Energy Association tracks and reports U.S. wind power industry employment in terms of full-time equivalents (FTE). This methodology and approach adjusts and accounts for part-time positions such as construction jobs that may only last a few weeks or months during the year or manufacturing positions that only work part-time on wind components.

Sources: AWEA 2014 [7], AWEA 2013 [53]

36. In the Iowa study, equipment and components that were purchased from other states or other countries are treated as monetary leakages and are not included in these estimates.

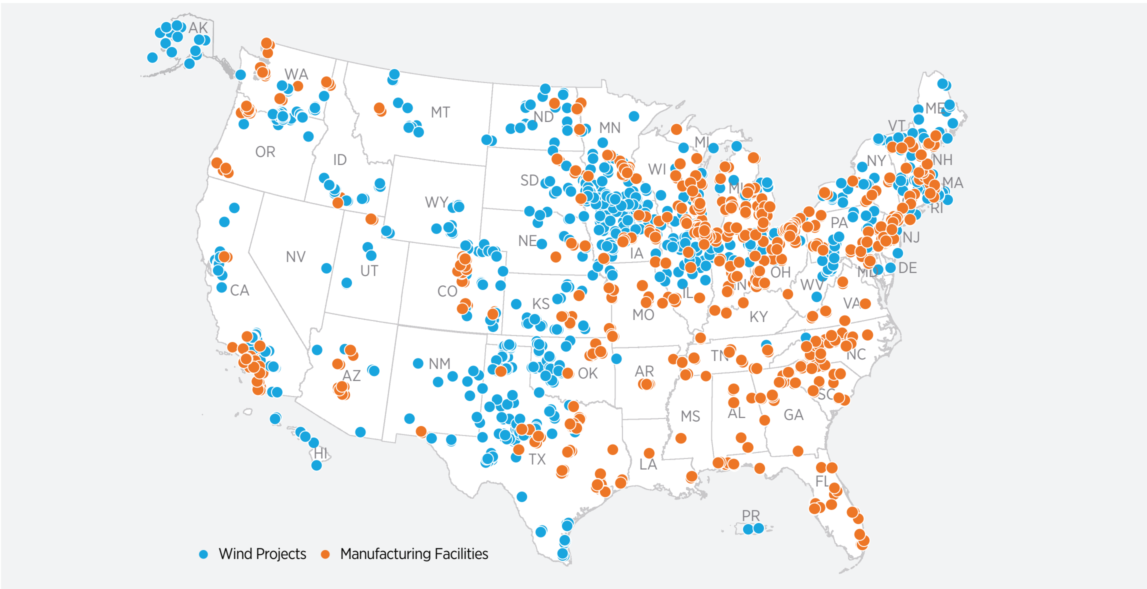
37. Results are in 2010 real (inflation-adjusted) dollars.

activity (Figure 2-20). Although only a little over 1 GW was installed in 11 states in 2013, by the conclusion of 2013 a record 12.3 GW were under construction in more than 90 projects across 20 states [7].

Job Training

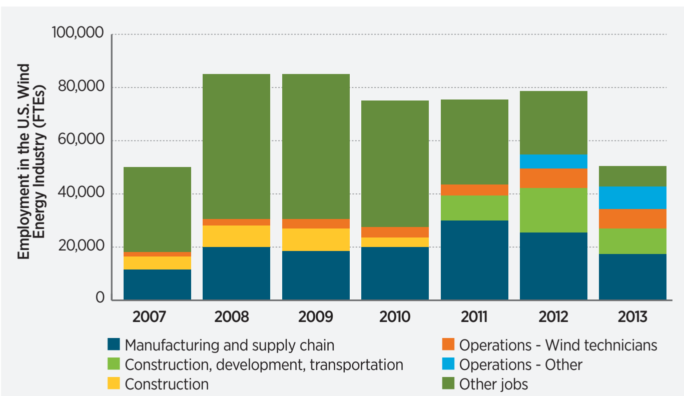
Most of the workers who participated in the rapid expansion of wind power development between 2002 and 2012 came from other market sectors. A 2012 industry survey [93], found that—except for specialized job professions, such as professors, research engineers, and technical specialists—wind-specific educational training was not required, but prior work experience in related fields such as construction or electrical work was considered important to wind industry employers.

By 2013, community and technical colleges were training students to become wind technicians, while an increasing number of universities offered wind power-oriented programs. University-level skill sets and fields needed by the wind power industry include engineering (e.g., electrical, aeronautical, material science, and mechanical), meteorology (e.g.,



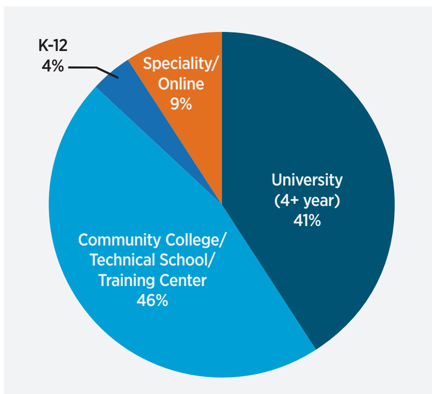
Source: AWEA [7]

Figure 2-20. Active wind-related manufacturing facilities and wind projects in 2013



Source: AWEA [7]

Figure 2-21. Types of jobs supporting wind power development, 2007–2013



Source: AWEA [53]

Figure 2-22. Types of institutions offering wind power programs wind resource assessment, microclimate impacts, and forecasting), biology (e.g., wildlife issues in siting projects), project management, business, law, and government policy (e.g., zoning, planning, and government administration professionals). There is also growing focus on workforce safety as the wind industry has expanded and matured. Text Box 2-5 describes some of the major safety-related activities the wind industry has undertaken.

Wind power education programs have increased at all levels since 2007. Most notably, community college technician training programs grew from six identified in the *2008 20% Wind Energy by 2030* report to more than 100 by 2012 [93]. Three U.S. universities offered a defined Ph.D. program in wind power in 2014 [93]. According to documents from the Executive Office of the President published in 2012, an expected shortfall in engineering graduates could be avoided with a 2012 government initiative to produce one million additional graduates with science, technology, engineering, and math degrees (Report to the Office of the President). The next generation is being exposed to

Text Box 2-5.

Workforce Safety

A number of factors affect safety in the wind industry. For instance, the workforce has varying degrees of experience and training in safety procedures. In addition, short lead times and erratic timing resulting from uncertain government policies and limited equipment availability may lead to rushed installation and commissioning of new wind generation facilities, increasing the potential for accidents and injury. Because most wind plant projects are in remote locations, the availability of adequately trained safety personnel or proximity to first responders may be limited, so continued and increased safety is an important consideration for the wind industry.

Due to the complexity of the worksite and the diversity of related equipment, several levels of procedural training are required for wind plant projects. This training includes personal safety as well as job-specific safety training. Training in safe climbing and self-rescue has become standard in the industry, and other skills such as first aid, CPR, automated external defibrillator use, basic fire safety, proper high voltage electrical safety, and qualified electrical worker training have also been incorporated and implemented. Most companies operating wind sites have developed minimum safety training requirements and are enforcing site rules for visitors and third-party technicians.

The wind industry has raised awareness of worker safety during construction, operation, and maintenance of wind plants. For example:

- AWEA signed an Alliance with the Occupational Safety and Health Administration in 2011 to share information and collaborate to develop compliance assistance materials for the wind industry.
- An AWEA Wind Turbine Risk Assessment subcommittee serves as a forum for owners/operators; original equipment manufacturers; independent service providers, including third party service providers; and other stakeholders to identify potential health and safety issues associated with non-proprietary wind turbine generator design, construction, operation, and maintenance.
- The AWEA Quality Working Group promotes quality assurance during the construction, operation, and scheduled and unscheduled maintenance of wind plants through the generation of tools specifically tailored to wind plant owners and their representatives.
- The AWEA Safety Committee addresses industry issues, such as ladder clearances and the sharing of safety incidents, data, and information among owner-operators.
- AWEA Wind Industry User Groups discuss safety and technical issues and challenges at face-to-face meetings and via pre-established distribution lists, e.g., ListServes.

possible careers in wind power through wind-related curricula at kindergarten through grade 12 schools (e.g., programs from KidWind, WindWise, and the National Energy Education Development Project) and schools that have installed wind turbines (e.g., through initiatives like Wind for Schools).[38] The rapid expansion of wind power in the United States from 2007 to 2009 also spurred efforts to retrain professionals from other industries to enter the wind workforce.

2.4.4 Air Pollution Impacts

No source of electricity is completely benign, and the ways in which wind deployment can impact humans and the environment are addressed later in this chapter as well as in Chapter 3 of the *Wind Vision*. Notwithstanding these local impacts, using wind power to offset fossil generation brings potential public health and environmental benefits, especially in the form of reduced air pollution. Wind power produces no direct air emissions and very low lifecycle emissions (see Chapter 3). Wind generation in 2013 was estimated to have avoided 157,000 metric tonnes (173,000 short tons) of SO_2 emissions and 97,000 metric tonnes (107,000 short tons) of NO_X [10].

Air pollution emissions of particular concern include not only SO_2 and NO_X (and particulate matter, or PM, formed in the atmosphere from those primary emissions), but also directly emitted particulate matter, mercury, and other toxins. In combination, these emissions have wide-ranging negative impacts on human health, economic activity, and ecosystems. In a 2011 rulemaking, the U.S. EPA wrote [94], "...2005 levels of $PM_{2.5}$[39] and ozone were responsible for between 130,000 and 320,000 $PM_{2.5}$-related and 4,700 ozone-related premature deaths, or about 6.1% of total deaths (based on the lower end of the avoided mortality range) from all causes in the continental United States. This same analysis attributed almost 200,000 non-fatal heart attacks, 90,000 hospital admissions due to respiratory or cardiovascular illness, and 2.5 million cases of aggravated asthma among children—among many other impacts." The National Research Council [95], estimated that in 2005, SO_2, NO_X, and particulate emissions from 406 U.S. coal-fired power plants caused aggregate economic damages of $62 billion, mostly from premature deaths associated with particulate matter created by SO_2 emissions. The same study found pollution damages from gas-fueled plants substantially lower, at $740 million.

Chapter 3 provides quantified valuation of the *Wind Vision Study Scenario* in reducing air pollution emissions. This valuation is complicated in part by the nature and stringency of future emissions regulations. Nonetheless, research suggests that these benefits may be substantial. For example, the Siler-Evans et al. [86] estimate the potential benefits of wind power in reducing the health and environmental damages of SO_2, NO_X, and $PM_{2.5}$ emissions from existing power plants. Wind generation is found to reduce air pollution damages valued from near 0.3¢/kWh (in California) to as much as 8.3¢/kWh (in Indiana), demonstrating the sizable range of potential benefits depending on the specific fossil plants displaced by wind power. As with GHG emissions, contemporary research has found that the variability of wind generation and the resultant cycling of fossil plants need not substantially offset wind's emissions reduction benefits (see Chapter 3).

2.4.5 Water Use

In arid parts of the country, water availability has already affected power plant development and operations for technologies other than wind, thus influencing the cost of electricity. Water use includes *withdrawal*, which is water diverted or withdrawn from surface water or groundwater but eventually returned to the source, and *consumption*, which is water that is withdrawn, consumed, and not returned to the source [96]. The power sector is the largest withdrawer of freshwater in the nation; power-sector water consumption is more modest, but can be regionally important. Electricity generation from wind does not use water in appreciable amounts and does not pose a direct systematic impact on water quality. This stands in contrast to thermal power plants (e.g., natural gas, coal, and nuclear energy), which require water for cooling [97]. Wind generation in the United States in 2013 is estimated to have reduced power-sector water consumption by 36.5 billion gallons, equivalent to 116 gallons per person in the U.S. [7].

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38. See the following for more information: Wind for Schools (*http://apps2.eere.energy.gov/wind/windexchange/schools_wfs_project.asp*), KidWind (*http://www.kidwind.org/*) and the National Energy education Development Project (*http://www.need.org/*)

39. $PM_{2.5}$ refers to fine particulate matter, i.e., articles less than 2.5 micrometers in diameter. Particles of this size are believed to pose the greatest health risks of all particulate matter.

Text Box 2-6.

Resource Diversity as a Motivation for Buying Wind Power

Public Service Company of Colorado, in reference to its contract with the 200-MW Limon II wind project: "Whenever wind power is generated from the Limon II facility, it will displace fossil-fueled energy on the Public Service system, mostly energy generated from natural gas. We think of this wind contract as an alternative fuel, with known contract pricing over 25 years that will displace fuels where the pricing is not yet known. That is the essence of the fuel hedge" [102].

Google, in reference to several long-term wind contracts into which it has entered: "We see value in getting a long-term embedded hedge. We want to lock in the current electricity price for 20 years. We are making capital investment decisions [regarding data centers] on the order of 15 to 20 years. We would like to lock in our costs over the same period. Electricity is our number one operating expense after head count" [103].

Georgia Power, in reference to its first two wind contracts: "Adding additional wind power to our generation mix underscores our commitment to a diverse portfolio that offers clean, safe, reliable, sustainable and low-cost electricity for years to come" [9].

Xcel Energy, in reference to 850 MW of wind contracts: "It works out to a very good levelized cost for our customers...These prices are so compelling, the energy [cost] associated with it is less than you can do locking in a 20-year gas strip" [9].

Public Service Company of Oklahoma, in reference to procuring triple the amount of wind power than originally planned: "The decision to contract for an additional 400 MW was based on extraordinary pricing opportunities that will lower costs for PSO's customers by an estimated $53 million in the first year of the contracts. Annual savings are expected to grow each year over the lives of the contracts" [9].

Studies evaluating the direct and life-cycle impacts of different forms of electricity generation have confirmed that wind has the lowest level of water use of any electricity generation technology (see Chapter 3 for more detail). One recent study examined total water usage of major energy generation technologies during plant construction, fuel production, and operations. This study determined that, throughout its life cycle, wind power has water use requirements that are orders of magnitude lower than the most water-efficient fossil fuel options [98].

The *20% Wind Energy by 2030* report showed that higher penetrations of wind power could further reduce water use from the power sector [18], an analysis that is updated and extended in the *Wind Vision* (Chapter 3). Power plant development and operations have already been impacted by water availability, especially in areas of the country in which water is scarce, such as the arid West and Southwest. This, in turn, influences the cost of electricity production. These impacts may be exacerbated in the future as a result of global climate change [99, 100]. In reducing water use, wind power can provide both economic and environmental benefits as discussed in Chapter 3.

2.4.6 Risk and Diversity

Risk and uncertainty are defining characteristics of energy supply: for example, fossil fuel prices are uncertain, federal and state regulations change, and electricity load cannot be known with certainty. **Based on several risk categories—construction cost risk, fuel and operating cost risk, new regulation risk, carbon price risk, water constraint risk, capital shock risk, and planning risk—Binz et al. [101] identified land-based wind as not only one of the lowest cost sources of new generation, but also as one of the lowest risk resources overall**. By supplying 4.5% of the U.S. electric power sector end-use demand in 2013, and more than 12% of supply in nine states, wind power is already contributing to a more diverse supply portfolio, thus reducing electric sector risk [7].

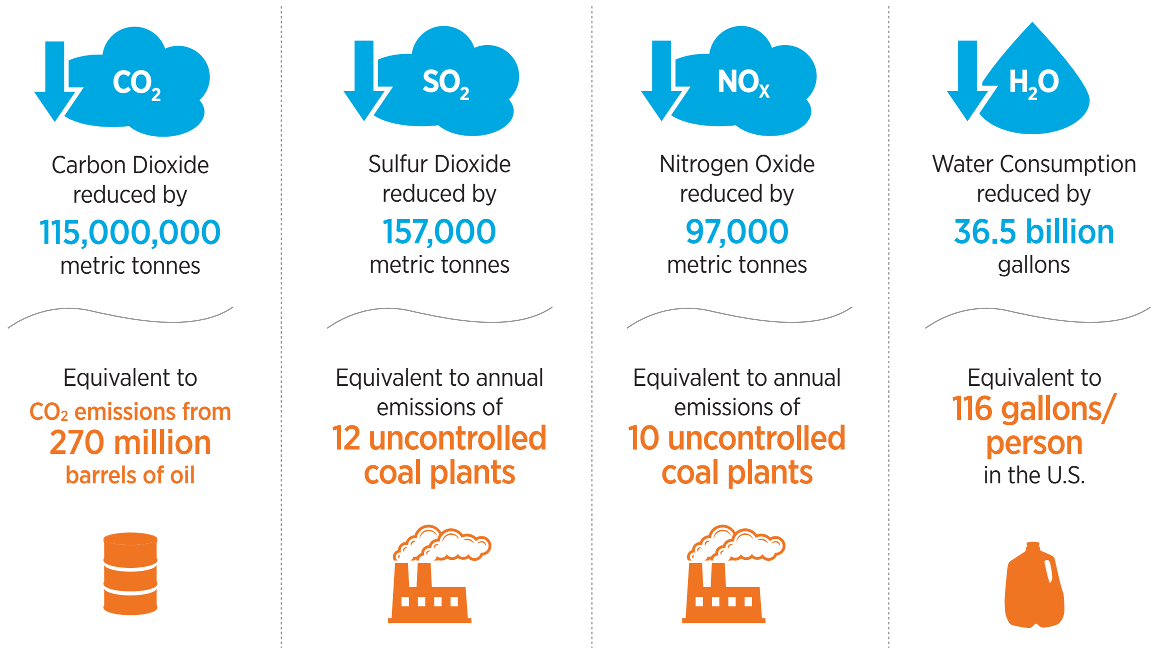
Quantifying the economic value of electricity supply diversity can be a challenge (see Chapter 3 for detailed discussion of this issue). Still, analysis demonstrates that wind can reduce the sensitivity of total energy costs to uncertain long-term changes in fossil fuel prices. As demonstrated by the quotes in Text Box 2-6, a variety of electric utilities and large energy consumers have noted the benefits of energy diversity as a driver for purchases of wind power.

By reducing demand for exhaustible fossil fuels, wind can also place downward pressure on fossil fuel prices, with benefits to energy consumers both within and outside of the electricity sector (i.e., consumers and electric utilities) [52]. This effect, as quantified for the *Wind Vision Study Scenario*, is addressed in detail in Chapter 3. At least in the short run, increased wind power can lower hourly wholesale electricity prices, benefitting electric utilities and consumers who purchase from those markets (albeit at the expense of producers). In a review of many studies, Würzburg et al [104] find a roughly 0.1¢/kWh reduction (within a range of 0.003-0.55¢/kWh) in wholesale prices per percentage penetration of wind power (see Chapter 3).

2.4.7 Conclusions

Wind power provides both economic and environmental benefits to the nation. Economic benefits of wind power are widespread and include direct employment, land lease payments, local tax revenue, and lower electric rates in wind-rich regions. Wind power plant provide jobs, a new income source for landowners (lease payments), and tax revenues for local communities in wind development areas. Utilities are using wind to mitigate financial risk within their portfolios with fixed-price contracts of long duration. Environmental benefits include substantial reductions in GHG emissions, air pollutants like SO_2 and NO_X, and water usage. In the United States, wind power is already reducing GHG emissions as part of the electric generation mix. As wind generation displaces generation from carbon-based fuels, harmful emissions and water use by power plants are also reduced. Figure 2-23 summarizes these emission and water savings.

The deployment levels in the *Wind Vision Study Scenario* require a highly skilled, national workforce guided by specific training standards and defined job credentials. This would enable a sustainable



Note: Emissions and water savings calculated using the EPA's Avoided Emissions and Generation Tool (AVERT). 'Uncontrolled coal plants' are those with no emissions control technology.

Source: AWEA [10]

Figure 2-23. Estimated emissions and water savings resulting from wind generation in 2013 workforce to support the domestic—and, as appropriate—the expanding international wind industry. Section 4.8, Workforce, discusses the *Wind Vision* roadmap actions, including the development of a comprehensive training, workforce, and educational program designed to encourage and anticipate the technical and advanced-degree workforce needed by the industry. Specific actions required include the development of a sustainable university consortium to support research and development efforts; technical training and student collaboration; implementation of an international academic network; creating sustainable wind-focused university programs; and expanding opportunities for student, industry, and university collaboration, such as internships, research fellowships, and joint research projects.

Objective and comprehensive evaluation of different policy mechanisms is needed to achieve wind power deployment that supports national energy, societal and environmental goals while minimizing the cost of meeting those goals in all three wind power markets: land-based, offshore, and distributed. Section 4.9, Policy Analysis, discusses three key areas in which the wind stakeholder community can collaborate to maintain the analysis capability necessary to inform policy decision makers. These collaborative efforts include comprehensively evaluating the costs, benefits and impacts of energy technologies; refining and applying policy analysis methods; tracking technology advancement and deployment progress; and updating the roadmap.

2.5 Wind Technology and Performance

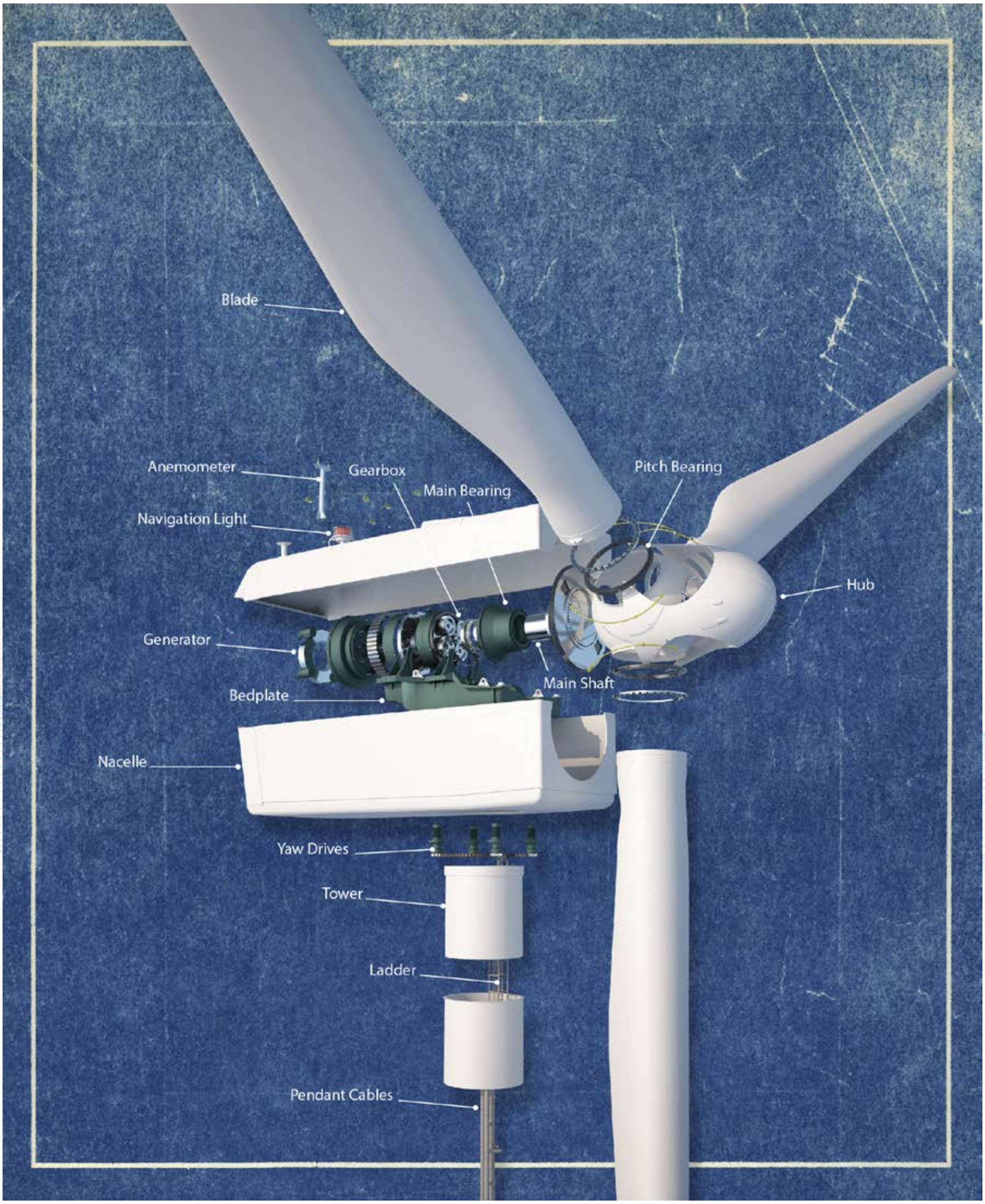
Several decades of technology development and deployed market experience have shown U.S. wind power to be a mature, reliable, and safe technology. Refined estimates raise the U.S. wind resource technical potential on land more than 40% over previous estimates and have increased the confidence level for offshore wind resource estimates [1]. Offshore wind technology has evolved out of land-based systems in Europe and is a major influence on worldwide technology trends. These trends include a push toward large turbines and unique support structures to handle hydrodynamic loading in the offshore environment. Better understanding of the wind resource and continued technology developments are likely to drive on-going trends in improved performance, increased reliability, and reduced cost of wind electricity.

Wind power systems include wind turbine components, individual wind turbines, wind plants comprising arrays of wind turbines, and the interaction of the wind power plant with the electric transmission and distribution grid systems.[40] Significant progress has been made in improving performance and reliability, and in reducing the cost of individual wind turbines. Industry efforts are now shifting to improving overall wind plant performance characteristics.

Technology development and improvements in reliability have helped drive a 33% cost reduction in land-based utility-scale LCOE from 2008–2013

Figure 2-24 illustrates the key components of a typical MW-scale wind turbine. The shape of the *rotor blades* is designed to efficiently convert the power in the wind into mechanical (rotational) power. The wind power that at any given wind speed can be captured by the *rotor* is proportional to its swept area, and larger rotors therefore capture more energy. One of the most complex systems in a wind turbine is the *drive train,* which converts the rotational power from the rotor into electrical power. A key component in the drive train is the *generator*. Most turbines utilize a *gearbox* to increase the rotational speed from the 5–15 revolutions per minute (RPM) of the rotor to the 500–1,800 RPM needed for typical generators. Some turbines omit the gearbox and instead use direct-drive generators that are designed to operate at very low rotor RPMs. Drive train components are housed in a *nacelle*, with the *rotor-nacelle assembly* installed at the top of a *tower*. The tower provides clearance between the rotor and the ground. It is important to note that wind speed generally increases with increased height above the ground, and taller towers therefore provide access to stronger winds.

40. Section 2.5 focuses primarily on utility-scale (1MW+) turbine technology. Small (<100 kW) and mid-sized (100 kw – 1 MW) turbine technologies share some similarities with utility-scale, but a more specific discussion on smaller turbine systems can be found in Section 2.3.



Source: National Renewable Energy Laboratory

Figure 2-24. Illustration of components in a typical MW-scale wind turbine

A wind power plant, or wind plant, is a set of wind turbines that are connected to the electrical transmission grid at a single point. In addition to the wind turbines, the wind plant contains many other components, including foundations for the towers, underground cables to collect the power from the individual turbines, step-up transformers, switchgear, roads, substation, and supervisory control and data acquisition (known as SCADA).

U.S. wind power resource potential, characterization, and future trends are summarized in 2.5.1. Wind plant technology status, including wind turbine scale-up, low wind speed technology, tower technology, blade technology, drive train technology, and control technology are discussed in Section 2.5.2. Section 2.5.3 discusses the current status and trends of wind plant performance and reliability, including capacity factor and the reliability of wind turbine systems, gearboxes, generators, and blades. Aftermarket upgrades, repowering and decommissioning are discussed in Section 2.5.4. Finally, offshore technologies are summarized in Section 2.5.5.

2.5.1 U.S. Wind Power Resource and Resource Characterization

The wind resource technical potential of the United States has been estimated to be 13 times current U.S. electricity end use. While these estimates of technical potential do not consider availability of transmission infrastructure, costs, reliability or time-of-dispatch, current or future electricity loads, or relevant policies, understanding this resource is crucial to tapping wind power.

Resource Potential

The United States has significant wind resources, both on land and offshore. At the time of the *20% Wind Energy by 2030* report [18], it was estimated that the U.S. wind resource technical potential was roughly 7,800 GW for land-based wind and roughly 4,400 GW for offshore shallow and deep water wind combined. These estimates were for turbines at a 50 m (164 ft.) wind tower hub height [105]. In general, the wind resource is better at higher levels above the ground. Refined estimates since 2008 take into account measurements at higher hub heights as well as technology improvements and place the U.S. land-based wind resource technical potential at 90 m hub heights (295 ft.) at roughly 11,000 GW, more than a 40% increase over previous estimates [1]. Offshore wind resource estimates are roughly 4,200 GW [1]. Though offshore estimates have not changed in magnitude with refined analysis, confidence levels for these estimates have improved. As noted, these are all estimates of technical potential and do not consider availability of transmission infrastructure, costs, reliability or time-of-dispatch, current or future electricity loads, or relevant policies. Technical potential estimates are based in part on technology system performance, so potential may change as technologies evolve.

Table 2-4. U.S. Wind Power Technical Resource Potential

	GW	TWh/ Year	Quad/ Year[a]
Land-based wind	11,000	32,700	112
Offshore wind	4,200	17,000	58
Total United States	15,200	49,700	170

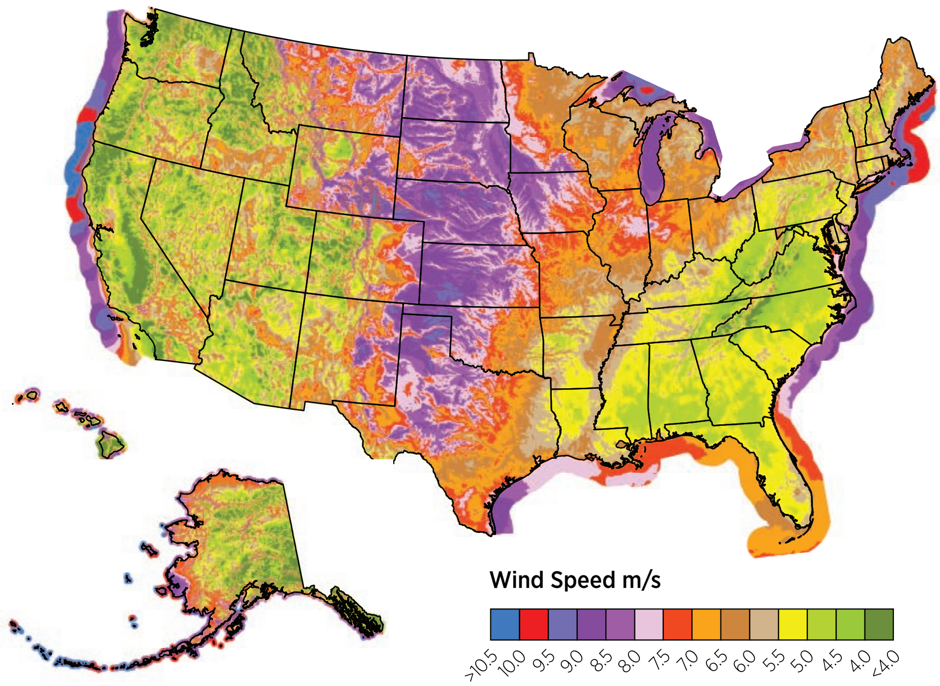
Note: Technical resource potential refers to technology-specific estimates of energy generation potential based on renewable resource availability and quality, technical system performance, topographic limitations, environmental, and land-use constraints only. The estimates do not consider (in most cases) economic or market constraints, and therefore do not represent a level of renewable generation that might actually be deployed.

a. 1 kWh = 3,412 Btu Source: Lopez [1]

The 20-year average of total U.S. primary energy use in all sectors combined is 96.2 quadrillion British Thermal Units (quads) per year, and was 95.0 quads in 2012, the most recent year for which data are available [3]. Of this, end-use electricity consumption was roughly 13 quads. The U.S. wind technical potential of over 15,000 GW is estimated to be able to produce 49,700 terawatt-hours/year, equivalent to 170 quads per year (Table 2-4), or 13 times U.S. electricity end use as of 2013.

These resources on land and offshore, combined with improved turbine and offshore wind technologies, provide the United States with vast wind power opportunities in every geographic region. Figure 2-25 illustrates the U.S. wind resource in terms of wind speed at a 100 m (328 ft.) hub height. More than 1,000 wind turbines have been installed on towers with hub heights of 100 m or more [7].

Improved computational capabilities and advances in wind speed measurement technology, especially remote sensing, have made high-resolution maps and fine spatial resolution databases available to the wind



Source: Wind resource estimates developed by AWS Truepower, LLC. Web: *http://www.awstruepower.com*. Map developed by NREL. Spatial resolution of wind resource data: 2.0 km. Projection: Albers Equal Area WGS84

Figure 2-25. Annual average U.S. land-based and offshore wind speed at 100 m above the surface

power community. Decreasing computational and data storage costs have allowed the use of more complex wind speed models to map the wind resource at higher spatial resolution on land and offshore, extending numerical domains to cover the entire continental United States with 2.5-kilometer (km) (1.55-mile) resolution. State maps have also been improved with finer levels of detail and at various heights above ground. These numerical resource assessments provide wind developers, utilities, and end users with useful supplements to data from meteorological towers and are an important tool for the detailed siting of wind turbines of all sizes.

Resource Characterization

Wind characterization is important for wind power development and wind plant design. Characterization of the wind, at a minimum, includes quantification of average wind speed and the variability around that average; quantification of seasonal and diurnal variations in the wind speed; wind direction and its correlation with wind speed; turbulence; and vertical shear. Making best use of available wind resources requires technology and operations optimization at both the wind plant and wind-grid system levels. Integral to system optimization is a complete understanding of atmospheric physics—the conditions and dynamics—and how these interact with wind turbine arrays in terms of structural loads and power production. The spatially and temporally dynamic interactions are known as "complex flow" [106]. Models for atmosphere, technology design, and wind forecasting as of 2013 do not accurately portray the atmospheric stability or complex terrain that determines turbulence affecting wind plants on the spatial and temporal scales necessary for forecasting wind. Efforts are underway to leverage federal high performance computing capabilities to develop and run models that can predict complex flow and its effect on and within wind plants both locally and regionally.

An important advance in wind speed measurement capability is remote sensing technology for recording wind speed and other characteristics from the ground. The most widely used types of this technology are Doppler and scanning LIDAR,[41] which uses atmospheric scattering of beams of laser light to measure

41. *Remote sensing* technology that measures distance by illuminating a target with a *laser* and analyzing the reflected light.

profiles of the wind at a distance. For land-based wind on flat topography, comparisons between Doppler, LIDARs, and tower-based wind measurements have been so favorable that LIDARs are being considered to provide reference wind measurements for wind plant production forecasts. Industry is investigating the use of look-ahead LIDAR systems to provide data on incoming winds before they arrive at the turbine. This can provide time for turbine control systems to adjust operation to match developing winds, an innovation that can increase energy capture and reduce loads during operations. For offshore applications, buoy-mounted LIDAR systems with sophisticated correction algorithms to allow for buoy motion promise to improve the quality of data collected while avoiding the cost of building measurement towers offshore.

Future Trends—Complex Flow

Improving the fidelity of the fundamental physics in computational models of the wind will improve wind plant power forecasts, which in turn will help optimize wind plant interaction with the transmission grid. Complex flow research will reduce errors in the representation of winds and turbulence near the ground in current models. Understanding complex flow is particularly important in mountainous terrain and coastal areas. Improvements in treatment of inflow and wake flows, turbine aerodynamics, and wind turbine technology will contribute to optimization of wind plants. Continued development of models and measurement techniques will contribute to improved wind turbine technology and lower LCOE. For example, new wind measurement technologies could provide readings throughout the rotor diameter of increasingly large wind turbines. Scanning versions of turbine-mounted LIDARs are being developed to optimize control in response to variation in wind inflow. Remote sensing measurements offshore can be used to eliminate the mast required for meteorological measurements and get bankable site data to lower risk and uncertainty at the project level, lower loads in conjunction with advanced controls, and validate wind resource models. DOE's "Atmosphere to Electrons" initiative, or "A2e," is designed to comprehensively address these complex flow issues, as well as the challenges of aerodynamic interactions between wind turbines operating in close proximity to one another within a wind plant. For more information, see Section 4.2 of the *Wind Vision* roadmap.

2.5.2 Wind Plant Technology Status

The scientific principles of modern wind turbine design and operation are well understood. As described in Section 2.1, continued technical improvement has reduced wind LCOE over time. This reduction, in combination with policy support and market barrier reduction, has led to rapid growth in wind deployment in the years leading up to the *Wind Vision*. Most utility-scale turbines being installed in the United States are three-bladed machines with controllable blade pitch, variable-speed operation, and computer controls. A yaw controller uses wind direction sensors for controlling the rotation, or yaw, of the nacelle around the tower and keeps the rotor facing the wind. The controller changes the orientation of the blades (pitch) when the wind speed is high enough to produce useful power (cut-in wind speed), and the rotor begins to spin. When the wind speed exceeds the speed required for the machine to produce its full rated power (rated wind speed), the blade pitch is increased to regulate the power output and rotor speed to prevent overloading the structural components. If wind speed exceeds design limits for turbine operation, the controller shuts down the machine by further increasing blade pitch.

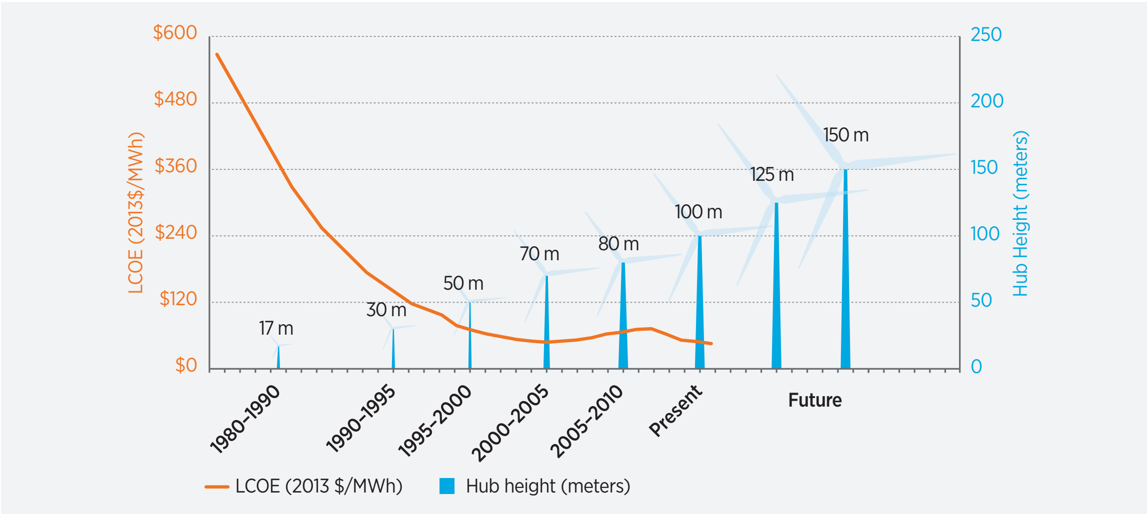
The amount of power in the wind available for extraction by the turbine increases with the cube (the third power) of wind speed; thus, a doubling of wind speed increases the available power by a factor of eight (2^3). The rotor and its associated controllers are designed to operate the turbine at the highest possible efficiency between cut-in[42] and rated wind speeds, hold the power transmitted to the drive train at the rated power when the winds go higher, and stop the machine in extreme winds. Modern utility-scale wind turbines generally extract about 50% of the available power in the wind at wind speeds below the rated wind speed, while the maximum power that a device can theoretically extract is 59% of the available power (the "Betz Limit"). Typically, a modern turbine will begin to produce power at a wind speed of 3–5 m/s and reach its rated power at 11–14 m/s. Around 25 m/s, the control system pitches the blades to stop rotation, feathering the blades to prevent overloads and protect turbine components from possible damage

42. Cut-in speed is the wind speed at which the turbine rotor begins to turn and the turbine begins to produce electricity.

due to high winds [18]. Some modern machines reduce rotational speed gradually in high winds to provide a gradual, rather than abrupt, reduction in power output as the wind speed increases.

Wind Turbine Scale-Up

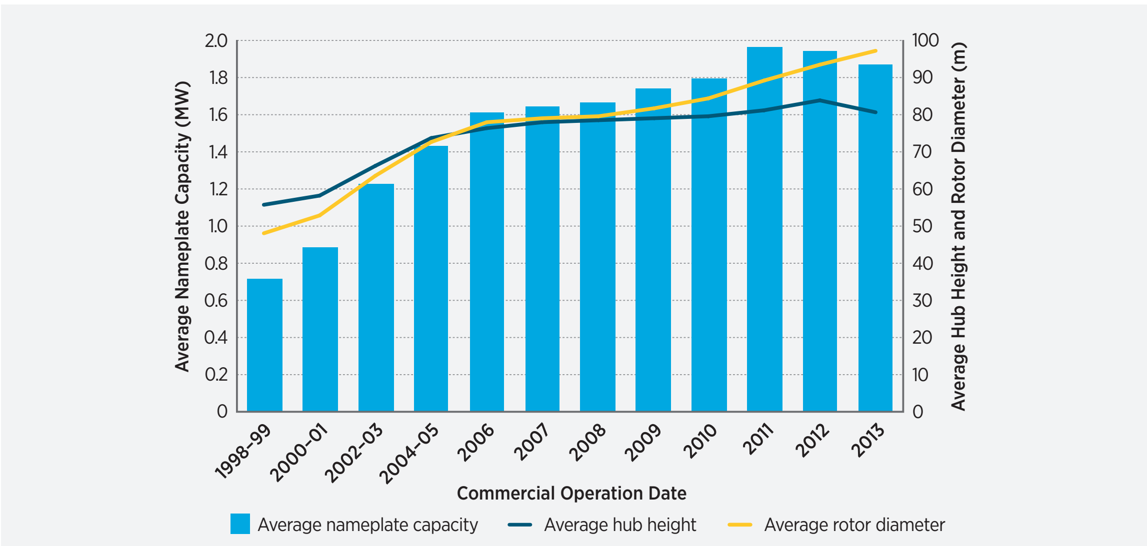
The average size and upper range of wind turbines installed in the United States has increased, with a period of rapid scale-up from 1998 to 2006 and again from 2009 to 2012 (Figure 2-26). In 2013, average nameplate capacity of utility-scale wind turbines was 1.87 MW, average rotor diameter was 97 m, and average tower hub height was 80 m [6]. Though there was a slight downtick in average hub heights from 2012 to 2013, this may be more attributable to the significantly smaller number of turbines installed in 2013 rather than an underlying trend (Figure 2-27).



Note: LCOE is estimated in good to excellent wind resource sites (typically those with average wind speeds of 7.5 m/s or higher), excluding the federal production tax credit. Hub heights reflect typical turbine model size for the time period.

Source: Wiser and Bolinger [6]

Figure 2-26. Wind technology scale-up trends and the levelized cost of electricity



Source: Wiser and Bolinger [6]

Figure 2-27. Characteristics of utility-scale land-based wind turbines 1998–2013

Low Wind Speed Technology (LWST)

The wind industry has begun deploying utility-scale projects using LWST with high hub heights and large rotors that allow greater energy capture even at sites with lower wind speeds.[43] In areas with less-energetic wind regimes, such as the Great Lakes region, the industry is installing turbines with towers taller than 100 m and rotors greater than 100 m in diameter [33, 25, 107]. LWST has become cost-effective through technical innovations in blade design and manufacture, as well as innovations in turbine controls that work to limit loads on key components. This trend in LWST is seen in General Electric's 1.5–1.8 MW wind turbines, where the rotor disc area per installed MW of generation capacity doubled between 2006 and 2013.[44] Wind turbines offered by other manufacturers show similar trends. As areas of higher wind resource are developed and constraints such as limited transmission capacity increase, the total potential developable area will become increasingly attractive for development with LWST. LWST can be used at good to excellent sites,[45] as well as at lower wind speed sites (average wind speeds of less than 7.5 m/s) such as those in the Southeast, Northeast, and portions of the West.

Tower Technology

Average hub heights for land-based turbines increased 46% from 1998 to 2013, growing from just over 55 m to 80 m. Energy capture at low wind speed and/or high wind shear sites is further facilitated by the use of tower heights of 100 m or more, which places the turbine rotors in higher average winds at most wind plants. Taller towers that reach higher winds could expand developable areas throughout the United States. The cost of towers, however, increases rapidly with increasing height, creating a trade-off between tower cost and the value of added energy production. Under current market conditions, technical innovations will be required for land-based tower heights beyond 120 m to be economical, since the installed cost increases faster than the energy production for most sites. In addition, Title 14 of the Code of Federal Regulations, Part 77, requires developers of all structures of 140 m and higher (including wind turbines) to file notice with the Federal Aviation Administration and undergo a public comment period before approval.

Rolled steel is the primary material used in wind turbine tower structures for utility-scale wind projects. Tubular steel tower sections are produced through automated manufacturing processes. Plate steel is rolled and machine-welded at the factory, then transported to and assembled at the project site.

Conventional rolled steel towers can be transported with tower sections up to 4.6 m in diameter over roads and 4.0 m via railroad. Tower diameters exceeding 4.6 m are difficult to transport. These transport restrictions result in sub-optimal tower design and increased cost for tower heights exceeding 80 m. A structurally optimized tower would have a larger base diameter, with thinner walls and less total steel. Overcoming this limitation would reduce project costs and LCOE.

New tower configurations are being evaluated to overcome transport limitations. These new configurations—known as hybrid towers—include concrete tubes for the lower, large-diameter sections and steel for the upper sections. Concrete towers have separate, pre-fabricated concrete elements with diameters up to 14.5 m. Large-diameter bottom segments can be produced as two or three partial shells that can be shipped on conventional transportation systems. Such towers could also have the concrete portions manufactured at the wind plant site. Research is also underway on fabric-covered space-frame towers that can also be assembled at the wind plant site, eliminating transportation constraints.

Blade Technology

Rotor blades have increased in length more rapidly than towers have grown in height, thereby increasing potential energy capture. Average land-based rotor diameters nearly doubled from 1998 to 2013, from less than 50 m to 97 m. Of the 582 turbines installed in 2013, 75% featured rotor diameters of 100 m or larger, a notable shift toward larger blades [7].

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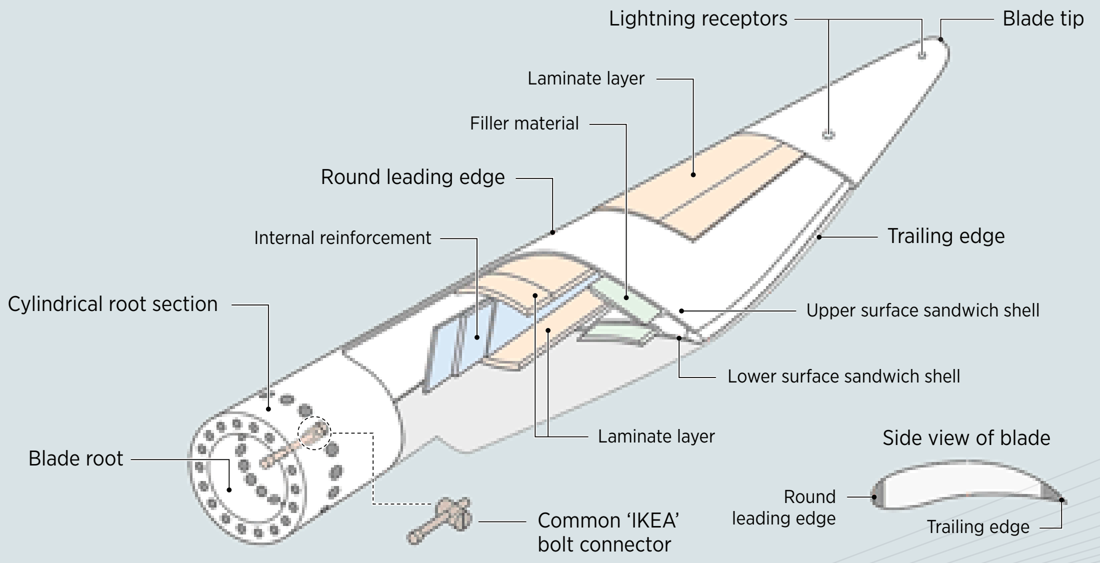
43. Annual average wind speeds as low as 6.0 m/s (13.4 miles per hour),

44. See product fact sheets at *https://renewables.gepower.com/wind-energy/turbines/full-portfolio.html*.

45. If there is no transmission available, a site may not be developable despite a high wind speed.



Source: Wind Power Monthly, July 2012

Figure 2-28. Turbine blade diagram

Optimizing LCOE through blade design involves tradeoffs between energy capture and turbine structural loads. Nearly all manufacturers have adopted full-span,[46] variable-pitch blades that regulate rotor power in high winds and reduce loads in extreme storms. Some manufacturers are moving away from blade geometries that are close to the aerodynamic optimum, sacrificing small amounts of energy capture to reduce structural loads and/or manufacturing costs and logistical constraints. The evolving designs feature much smaller maximum chord dimensions (the longest line joining the leading edge to the trailing edge) near the root of the blades. These blades are less expensive to manufacture and are easier to transport on conventional trailers or by rail. Also, reduced chords over the outer 1/3 of the blade span can significantly reduce structural loads, with only small reductions in energy capture, reducing the overall cost of energy. Reducing the outboard blade area only slightly decreases energy capture but significantly reduces structural loads and physical dimensions, resulting in manufacturing and transport cost savings. The industry is exploring rotor blades that can be delivered to a wind plant in two or more pieces and assembled on-site, which would enable the continued growth of rotor diameters.

Another advancement in blades and rotors is innovative airfoil designs to achieve specific goals, such as maximum thickness and aerodynamic performance. Airfoil sections with blunt trailing edges, known as flat back airfoils, have been deployed for the inboard region of large wind turbine blades because they provide structural advantages. Vortex generators near the root have been used to reduce the adverse effects of flow separation. Specially-designed airfoils have been developed and used near the tip to reduce noise.

Advanced materials are being used to manufacture lighter blades, including carbon fiber in structural spar caps, and sophisticated engineered cores. Other novel blade configurations are under development that use aero-elastic tailoring to alter the blade geometry in response to high-load wind conditions in a manner that reduces the loads.

The growing trend of making several blade lengths available for the same basic turbine has contributed to the lower cost of wind power. This, along with variations in the tower height, permits turbines to be customized for specific conditions at each wind plant. This approach can better optimize the trade-offs between energy capture and structural loads.

46. In a full-span configuration, the entire blade changes pitch.

Drive Train Technology

The drive train converts a rotor's rotational power into electrical power and generally includes a main shaft, a gearbox (unless a direct-drive configuration is used), a generator, and a power converter. As of 2006, most utility-scale wind turbines used a three-stage gearbox to convert the power of the rotor blades (low rotational speed, high-torque) into high-rotational-speed, low-torque power suitable for a conventional high-speed generator operating at 1,200–1,800 RPM [108]. By 2013, most utility-scale turbines used variable-speed technology. Variable-speed turbines can extract more energy at low wind speeds and impose lower structural loads at higher wind speeds than constant speed generators. In variable-speed turbines, rotor speed is controlled using blade pitch and power electronics to alter the frequency of the generator field.

Continued advancements in drive train technology can decrease maintenance and related costs, which will in turn reduce LCOE. Additional drive train technology developments since 2006 include:

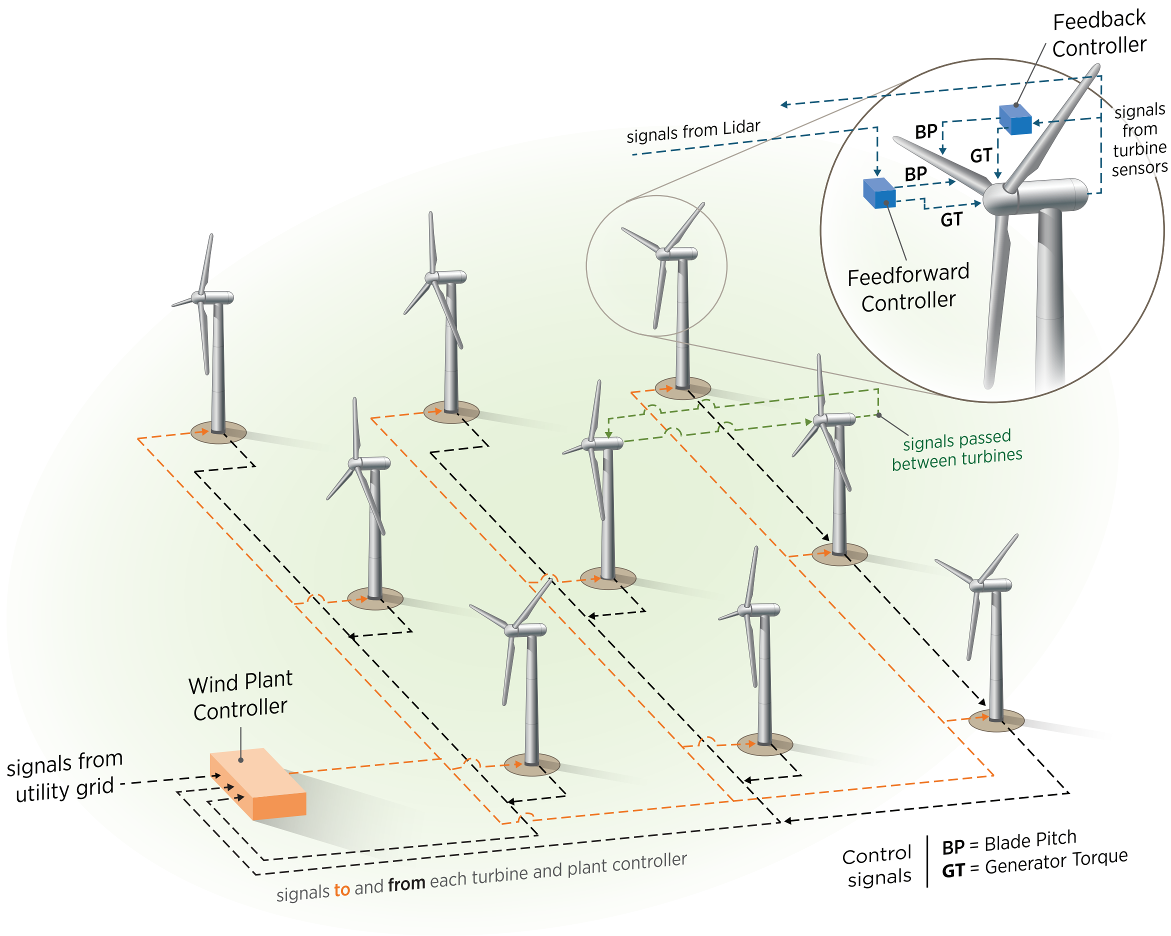
- **Direct drive** generators that eliminate the need for a gearbox. Direct drive turbines comprised 3.3% of new U.S. capacity installed in 2012 (194 turbines totaling 429.7 MW), an increase from 17 direct drive turbines installed in 2011 (totaling 35.3 MW) and no more than three such turbines per year from 2008 to 2010. Direct drive technology has been relatively slow to enter the U.S. market in comparison to global trends—28% of global wind turbine supply in 2013 featured direct drive turbines [6].
- **Permanent magnet** synchronous generators with improved efficiency based on rare-earth materials. These generators are used in conjunction with high-speed gearbox designs as well as direct-drive, gearbox-free turbines.
- **Medium-speed** single-stage drive trains with generators operating at approximately 100 RPM.
- **Main shafts** with dual bearings or a non-rotating kingpin to support the hub and isolate the gearbox from rotor loads.
- **Full power conversion** technologies that increase the range of variable rotor speeds, further improving energy capture at low wind speeds.

Control Technology

Wind plants consist of large arrays of wind turbines connected through a single point to the transmission grid. Controls for wind turbine speed, power output, and other characteristics, however, have been used largely for individual machines in response to turbine-based criteria. These controls allow operators to manage and monitor turbines remotely, from the site's O&M station as well as from regional and global remote operating centers. More advanced control technology now includes active controls to sense turbulence-induced rotor loads and alter turbine operation to reduce these loads (Figure 2-29). Controlling all turbines within the plant to maximize total production and reduce loads could result in lower LCOE.

Wind turbine controllers integrate signals from dozens of sensors on or around the turbine to control rotor speed, blade pitch angle, generator torque, and power conversion voltage and phase. The controller manages critical safety measures, such as shutting down the turbine when extreme conditions are encountered. Electrical controls combined with power electronics enable turbines to deliver fault ride-through operation, voltage control, and volt-ampere-reactive support to the grid. As with other ancillary services and providers, the necessary incentives must be in place to encourage this flexibility. Research is underway on wind turbine active power controls and market incentives necessary to induce the provision of these flexibility services when they are cost-effective. Active power control allows the power system operator to control the wind generator output when there is excess energy or when fast response is required to maintain reliability.

Advancements in individual turbine sensor technology include built-in condition monitoring systems that measure vibrations or oil particle count in key areas of the drive train. The vibrations are tracked continuously. When the signature of the vibration changes, a notice of non-standard operating conditions is sent to operators, allowing them to take precautionary measures such as shutting down a turbine until inspection and repair can occur. Condition monitoring systems have enabled operators to make proactive minor repairs up-tower without a crane before failure of one component affects others, reducing costs and downtime.



Source: National Renewable Energy Laboratory

Figure 2-29. Wind plant controls, including LIDAR sensor signals for feed-forward control and integrated wind plant control

Advanced controls have improved turbine and wind plant performance and reliability. Such controls also offer some of the best opportunities for reducing LCOE. Advanced turbine controllers can accommodate larger rotors and increased energy capture for a given drive train without changing the balance-of-system requirements. Several approaches are used, including model-based control; multiple-input, multiple-out systems; and micro-tuning of turbine controls for specific wind plant sites. These advanced methods are often used with passive load reduction technologies developed for longer rotor blades.

Individual blade pitch control is another advanced control scheme. While collective pitch control adjusts the pitch of all rotor blades to the same angle, individual blade pitch control dynamically and individually adjusts the pitch of each rotor blade in real-time based on measured loads. The main benefit of individual blade pitch control is the reduction of fatigue loads on the rotor blades, the hub, and mainframe and tower structures. In order to reduce these loads, especially asymmetric loads caused by heterogeneous wind fields, the pitch of each rotor blade has to be adjusted independently from the other blades. A reduction of fatigue loads has two considerable advantages: it allows lighter designs and can translate into increased reliability [109]. Individual blade pitch control systems are currently in service on some modern turbines. The innovation permits higher wind conversion efficiency, which translates to lower LCOE for wind power.

Research is also underway to develop plant-wide controls to optimize overall wind plant output. This innovation presents the opportunity to improve overall plant-level energy capture and reduce structural loads by operating the wind turbines in an integrated fashion. Another way controls can contribute to wind deployment is by using active power control of the entire wind plant in a way that improves overall grid stability and frequency response and regulation. Active power control helps balance load with generation at various times, avoiding erroneous power flows, involuntary load shedding, and machine damage. This technology, discussed in more detail in Section 2.7, could change the paradigm for the integration of wind turbines onto the transmission grid [110], further expanding deployment opportunities.

Future Trends—Plant Technology

Continued advancements in wind power technology will drive reductions in LCOE and facilitate wind deployment in new markets, such as low wind speed areas. Some key on-going trends include:

- **Towers:** Transportation, logistical, and regulatory issues must be addressed in order to deploy taller towers to enhance wind resource access. On-site manufacture or assembly of towers provides a key opportunity. As previously discussed, all structures higher than 140 m (including wind turbines) must file notice with the Federal Aviation Administration and undergo a public comment period before approval.
- **Blades:** The development of efficient multi-piece blades that can be economically transported to new wind plants will enable further growth in rotor diameters. The development of low-cost carbon fiber material systems will play a key role in the design and manufacture of these larger rotors.
- **Drive trains:** Increasing diversity in drive train configuration—including geared, medium-speed and direct-drive technologies—is expected to continue. Drive train configurations are expected to have increased reliability and service life, and greater overall efficiency. Power electronics systems will provide increasingly valuable grid services, such as frequency regulation and synthetic inertia.
- **Controls:** Given current technology trends, wind plants will increasingly be controlled and operated as an integrated system, enhancing reliability and energy capture, and improving grid stability. Innovations in turbine-level control systems, such as feed-forward control, will continue to enable increases in rotor size without commensurate increases in structural loads. Research will continue on wind turbine active power controls and the market incentives necessary to induce the provision of these services (i.e., when they are cost effective).

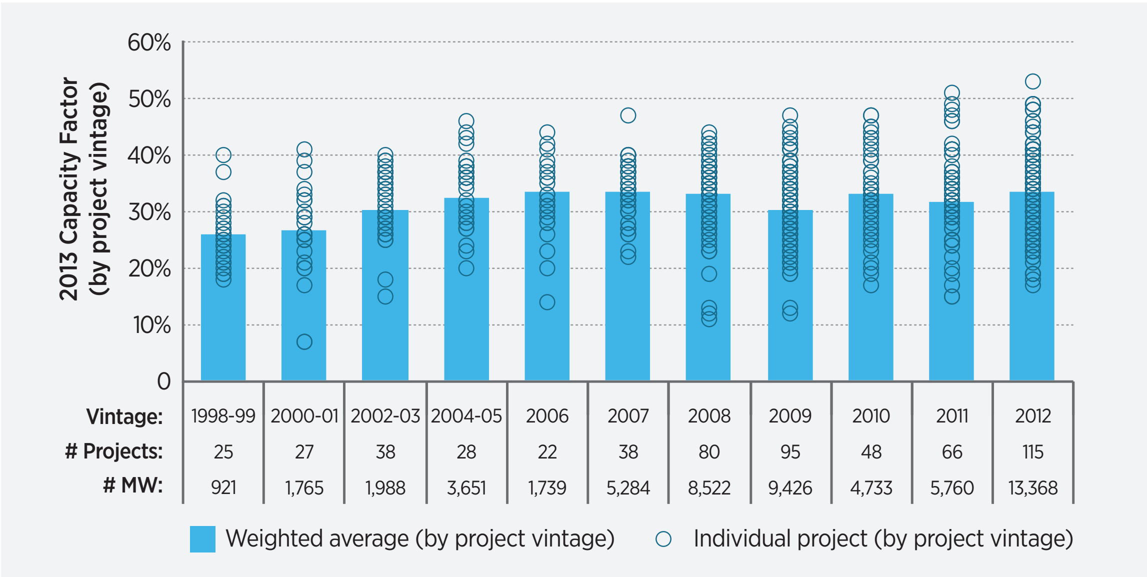
2.5.3 Wind Plant Performance and Reliability

Cost drivers for LCOE include wind turbine and wind plant performance, as measured by annual energy production and capacity factor. Wind turbine reliability in terms of scheduled and unscheduled O&M and component replacement is also an LCOE driver, and improvements offer opportunity for reductions in LCOE and technical risk.

Capacity Factor

As noted, capacity factor is a measure of the productivity of a power plant. It is calculated as the amount of energy that the plant *actually* produces over a set time period divided by the amount of energy that *would have been* produced if the plant had been running at full capacity during that same time interval. Wind project capacity factors have been higher on average in more recent years (e.g., 32.1% from 2006 to 2013, versus 30.3% from 2000 to 2005). Time-sensitive influences—such as inter-year variations in the strength of the wind resource or changes in the amount of wind power curtailment—may mask the positive influence of turbine scale-up on capacity factors in recent years [6].

Variations by project vintage year occur due to countervailing trends of larger rotor diameter, which tends to increase capacity factor, and increasing installations in lower wind resource sites, which tends to reduce capacity factor. These trends have overshadowed the potentially large positive effect of technology improvements such as larger rotors, taller towers, and sophisticated controls on capacity factors. As shown in Figure 2-30, a few outlying individual projects show capacity factors above 40%, with a few exceeding 50% [6]. Variances in capacity factor can be influenced by:



Note: Sample includes 582 projects totaling 57.2 GW

Source: Wiser and Bolinger [6]

Figure 2-30. Wind project capacity-weighted average capacity factors for 2013 by commercial operation date for project vintages 1998–2012

- **Regional Differences:** Design changes such as larger rotors and taller towers can open new resource areas to utility-scale wind projects with capacity factors sufficient for cost-effective development. Data indicate average regional capacity factors for utility-scale wind projects built in 2012 were highest in the U.S. Interior (38%), and lowest in the West (26%). These regional differences can be explained by differences in wind resources and by varying types of deployed wind turbine technology. A lower specific power rating[47] for a turbine yields a higher turbine capacity factor. For turbines installed 2011 to 2013, 30% of all turbines installed in the Great Lakes region had a specific power rating less than 220 watts per square meter (W/m^2), vs. 5% of the turbines in the Western region.
- **Curtailment:** National wind power production can be reduced by curtailment, where the dispatch order from the transmission system operator to the wind plant is to reduce or stop generation even though the wind resource is available. Some reasons for curtailment, such as transmission constraints, are discussed in Section 2.7. Operators may also voluntarily curtail production in response to price changes. The United States has many balancing areas,[48] each of which may have its own curtailment practices. Though curtailment varies by balancing area, in aggregate curtailment has declined to 2.5% of total wind power generation in 2013, down from a peak high of 9.7% in 2009. Specifically, only 1.2% of potential wind power generation within the Electric Reliability Council of Texas (ERCOT) was curtailed in 2013, 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 and a move to more-efficient wholesale electric market designs [6].

47. The "specific power" of a wind turbine is the ratio of generator nameplate capacity (in watts) to the rotor-swept area (in m^2). With growth in average swept area outpacing growth in average nameplate capacity, there has been a decline in the average specific power (in W/m^2) among the U.S. turbine fleet over time, from around 400 W/m^2 among projects installed from 1998–2001 to 253 W/m^2 among projects installed in 2013.

48. A balancing area is a predefined area within an interconnected transmission grid where a utility, an independent system operator, or a transmissions system operator must balance load (electrical demand) and electrical generation while maintaining system reliability and continuing interchanges with adjoining balancing areas. An interconnected grid can have one or many balancing areas. For example, the Western Interconnection, which covers much of the western U.S. and western Canada, has 35 balancing areas, while the Texas Interconnection only has one.

Wind Turbine System Reliability

Relative to capacity factor, turbine downtime has a relatively smaller impact on LCOE, with availability rates[49] of greater than 98% as of 2013 [25]. Replacement of failed components can cost hundreds of thousands of dollars, due to the cost of the components as well as the rental costs of large cranes, and can result in lost revenue from lost production time. European WindStats data from 2008 to 2012 show a decrease in turbine downtime due to gearbox, electric system, and generator failures, but an increase due to rotor failures [111]. Separately, the European Reliawind project found electrical systems, pitch systems, and yaw systems to be the largest drivers of turbine downtime [112]. One of the challenges in understanding trends in component failures is that turbine reliability is affected by many factors including equipment quality, operating conditions and maintenance, and the age of turbines. Improving wind turbine component, sub-system, and system reliability can reduce costs for O&M and replacement of components, as well as reducing downtime. Better tools have been developed to predict remaining useful component life and verify the accuracy of the prediction of fatigue life for new turbines.

Table 2-5. Aggregated Utility-Scale Wind Turbine Downtime by Turbine Subsystem for 2007 and 2012

Downtime by Subsystem (%)	2007	2012	Variation from 2007 to 2012
Subsystems with Decreasing Downtime Trends			
Gearbox	30.9	9.9	-21.0
Electric system	15.7	6.4	-9.3
Generator	13.2	4.3	-8.9
Pitch adjustment	9.9	1.8	-8.1
Main shaft/bearing	6.7	5.8	-0.9
Hydraulics	5.8	3.1	-2.7
Air brake	5.5	1.8	-3.7
Sensors	2.4	1.8	-0.6
Mechanical brake	0.8	0.1	-0.7
Subsystems with Increasing Downtime Trends			
Electric controls	4.5	5.2	0.7
Rotor	2.9	6.1	3.2
Yaw system	1.6	5.6	4.0
Windvane/anemometer	0.1	1.0	0.9
TOTAL	**100**	**52.9**	**-47.1**

Note: Total turbine downtime in 2012 was 47.1% less than turbine downtime in 2007. Changes in 2012 total turbine and subsystem downtime are measured as a percentage of the 2007 total turbine downtime.

Source: National Renewable Energy Laboratory and Wind Stats, data from 2007 to 2012

49. The availability factor of a *power plant* is the amount of time that the plant is able to produce *electricity*, divided by the amount of time in the period.

Gearbox Reliability

A 2013 summary of insurance claims revealed that the average total cost of a gearbox failure was $380,000 [113]. An analysis of 1000 turbines over a 10-year period reported that 5% of turbines per year required a gearbox replacement [29]. Gearbox reliability remains a challenge for utility-scale wind turbines, though trends in Table 2-5 indicate that reliability has improved since 2007. The industry uses a systems approach as the most effective for improving this aspect, with attention to reliability integrated throughout the design, manufacturing, commissioning, and O&M stages [114]. Through collaborations, diagnostics, and accelerated testing, the industry has gained a better understanding of the most frequent gearbox failure modes and possible root causes. Researchers have confirmed that a key factor contributing to premature gearbox failures is that bending loads (rather than torque loads) on the input shaft cause excessive loads on the gears and bearings. Tapered roller bearings have been incorporated into the planetary design, and new main bearing and main shaft design strategies have been adopted to reduce non-torque loads transmitted to the gearbox. It has become standard practice to perform extensive dynamometer testing of new gearbox configurations to prove durability and reliability before introduction into serial production [18]. Such dynamometer tests have identified design or material weaknesses that were remedied before field testing or production.

Condition monitoring systems mounted on parts of the drive train are becoming more common, enabling detection of problems earlier and minimizing downtime. Gearbox repairs or part replacements are more often performed up-tower. This avoids the need for a crane to lower components to the ground, thereby reducing maintenance costs. Refinements in materials, quality, metallurgy, surface finishing, and lubricants are all considered in efforts to improve gearbox reliability.

Generator Reliability

A generator failure in 2013 was estimated to cost $310,000 [113], while an estimated 3.5% of turbines required a generator replacement [29]. Data from U.S. wind plants reveal that electrical winding and bearing failures are the two largest sources of downtime for generators. Electrical winding failures result from a combination of improper specification and design issues, manufacturing inconsistency, or quality issues. Environmental conditions and poor electrical power quality exacerbate generator reliability problems. Bearing failure is the single largest contributor to generator unreliability and is probably influenced by multiple mechanical root causes: improper lubrication, machine misalignment, and transient electrical current damage [115]. Original equipment manufacturers have pursued direct drive turbines to avoid misalignment problems, but to date there have been no published studies in the United States to confirm improved reliability and lower operating costs of direct drive turbines. Generator manufacturers often make upgrades and revisions to address identifiable failure modes. These changes might include cooling system improvements, bearing design changes, and other insulation and structural improvements based on the results of electrical and mechanical testing.

Rotor Reliability

Average replacement costs for a blade failure are estimated at $240,000 [113], with 2% of turbines requiring blade replacements annually [29]. With larger blades being used on wind turbines, weight and aeroelastic limitations have put added pressure on blade design and manufacturing, which may be one of the explanations for the uptick in rotor-driven downtime reported in Table 2-5. Blade failure can arise from manufacturing and design flaws, transportation, and operational damage. Manufacturing flaws include fiber misalignment, porosity, and poor bonding. During transport from the manufacturing plant to the wind plant site, blades can undergo several lifts, which result in localized loads that can cause damage if not properly executed. Operational damage is primarily related to either lightning strikes or erosion of blade leading edges.

Testing of composite material coupons and sub-structures to determine the effect of manufacturing defects has increased both in research and industry [116]. Manufacturers increasingly use non-destructive inspection[50] practices to assess the quality of blade structures, especially critical sections like spar caps. Non-destructive inspection techniques have been found effective in finding several common defects, including dry spots, delaminations, and gaps in adhesive bonds. Improvement in inspection and repair techniques, coupled with the high cost of blade replacement, has led the industry to move towards repairing damaged blades. The development

50. Non-destructive inspection uses techniques that do not cause harm when evaluating materials, components, or systems.

of in-situ blade inspection technology and processes could become an alternative to manual inspections, improving reliability and technician safety. Ultimate-load and fatigue testing of full-scale blades are standard and required for design certification, with continuous improvement in load calculation and testing methods. The international blade design standard, IEC 61400-5, will outline in more detail what is needed to design and maintain blades for reliability. Blade testing, whether at government or private laboratories, is critical to design blades to meet expected lifetimes, because it can diagnose design or manufacturing errors which cause early and sometimes catastrophic failures. Blade test methods are continuously improving, as are design methods and manufacturing processes. For more information about testing, please see Appendix F, Testing Facilities.

2.5.4 Aftermarket Upgrades and Repowering

Most original equipment manufacturers offer aftermarket upgrades to improve wind turbine and wind plant performance of installed fleets. Some example upgrade products include modifications to turbine control parameters that allow an increase in maximum power output; vortex generators, which use small fins to optimize air flow over the blades and improve aerodynamics; and software improvements that support self-diagnosis of subsystem components and increase turbine availability. These aftermarket products are added to existing equipment to improve performance, but do not extend the useful life of the original turbine.

Repowering wind turbines occurs when equipment at a wind plant is replaced with newer, higher-performing turbines that increase the capacity factor using technologies not available when the original plant was constructed. A wind plant is typically repowered at the end of its useful life, and most original equipment manufacturers certify turbines for a 20-year lifetime. The significant increase in wind turbine power ratings since the early 1990s creates a financial incentive to repower high quality wind resource sites with new turbines. This incentive needs to be balanced against site-specific requirements in updating the balance of system elements such as the roads, foundations and potentially the grid connection equipment.

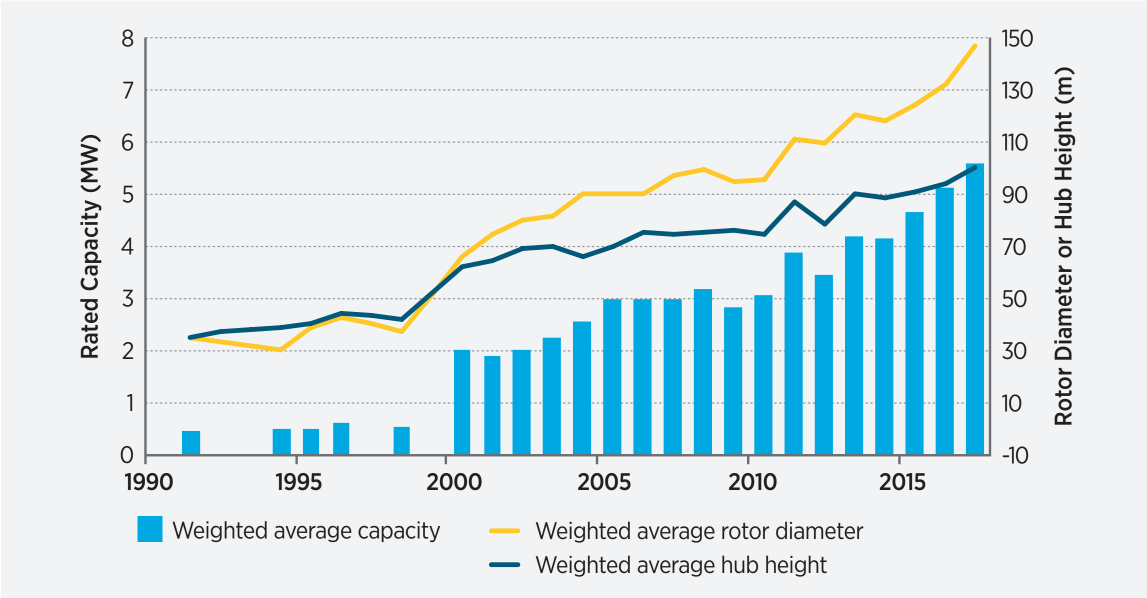
As of 2012, 75% of installed wind plant capacity (52% of installed turbines) was less than five years old, and 8% of installed capacity (34% of installed turbines) was older than 10 years [117]. As these installed assets age, the market for repair, replacement and repowering grows. While regulatory issues in California in the early 2000s prevented significant repowering activities, new policies have improved the repowering market. See Section 3.3.1, Capacity Additions, in Chapter 3 for more information.

2.5.5 Offshore Technology

Offshore wind technology can take advantage of many of the same technology developments described for land-based systems. These areas include array optimization strategies, turbine architectures, advanced composites, aerodynamics, and controls. There are many technology areas, however, in which offshore wind technology is progressing along unique pathways independent of land-based drivers. Offshore wind turbines

- are trending toward larger turbines twice the size of their land-based counterparts;
- demand higher reliability due to vastly more challenging accessibility;
- rely on subsea power cable networks and substations far from land; experience significant hydrodynamic loading; and
- are coupled to a range of support structures, including floating systems that are highly dependent on water depth.

New technology is expected to contribute to offshore wind cost reductions, which can be realized through lowering capital cost, increasing energy production, increasing reliability, and lowering the risk profile for investors. The turbine comprises just 30% of the total capital cost of an offshore wind project, while the balance of system and associated project construction costs represent the remainder [118]. A major technology trend since 2008 has been to develop larger, 5–7 MW capacity turbines. These larger turbines enable greater balance of system cost reductions (foundations and marine construction) on a per MW basis because they allow for fewer foundations, less cable, lower O&M, and more MW per unit area. Most major offshore turbine suppliers are developing larger turbine models specifically for offshore. These turbines



Source: National Renewable Energy Laboratory

Figure 2-31. Average turbine size, rotor size, and hub height for commercial offshore wind plants

are entering the market as prototypes or as early stage commercial production units. Transportation and erection restrictions limit the use of these turbines in land-based applications, so their introduction has resulted in new supply chains unique to offshore wind, especially for components like large blades and nacelles. Figure 2-31 shows the historic and projected average turbine size, rotor size, and hub height for installed offshore wind projects.[51] Projections are based on projects approved as of 2013.

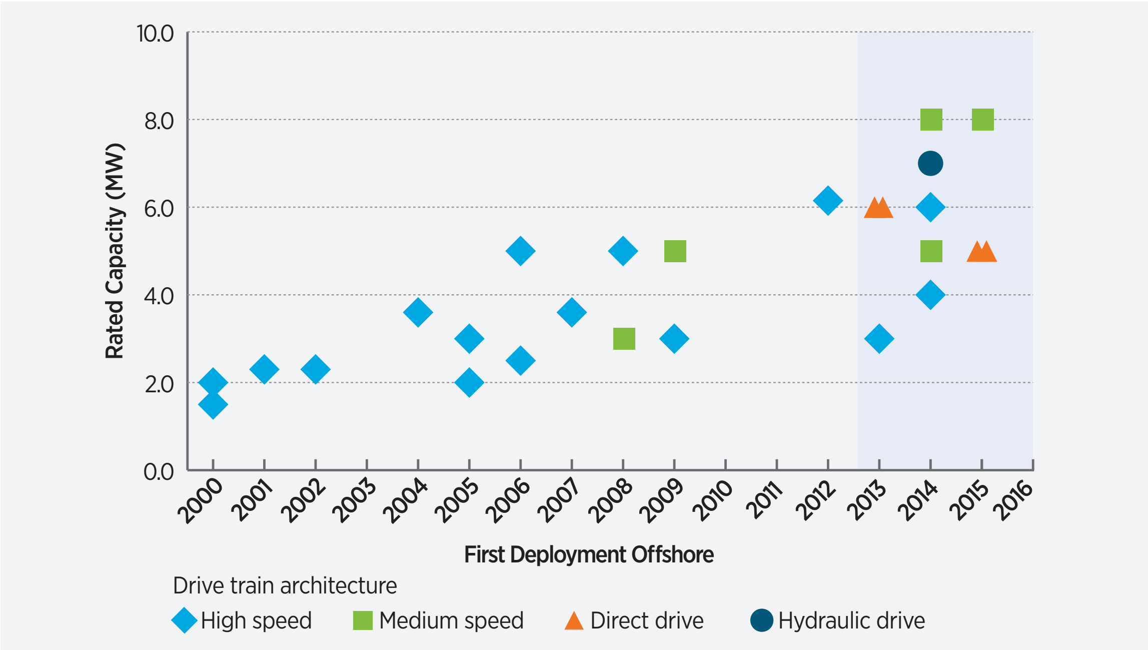
The introduction of larger turbines in European waters has also stimulated the development globally of vessels, equipment, and infrastructure with the capability to install these machines. These new vessels require cranes with maximum lift heights approaching 130 m and lifting capacities between 600 and 1,200 tons, suitable for larger turbine models [119].

This emerging fleet of offshore wind turbines is also characterized by a move toward gearless direct drive generators and single-stage geared systems with medium-speed generators (Figure 2-32). These direct-drive and medium-speed generators take advantage of innovative technologies in rare earth permanent magnets that allow lighter nacelle weights, created with lower fabrication and maintenance costs in mind. Design innovations under development include modularity of the generator poles, superconductivity, switched-reluctance, and power conversion incorporated into generator modules. New designs have demonstrated a reduction in top mass, thereby reducing weight of all support components.

Direct-drive generator technologies could be favored more in offshore applications because they reduce the total part count, which theoretically could lower offshore maintenance costs. Since offshore wind turbines are remote and accessibility is limited by weather and high vessel costs, offshore wind maintenance strategies also place a higher emphasis on remote sensing, condition monitoring, and optimizing weather windows.

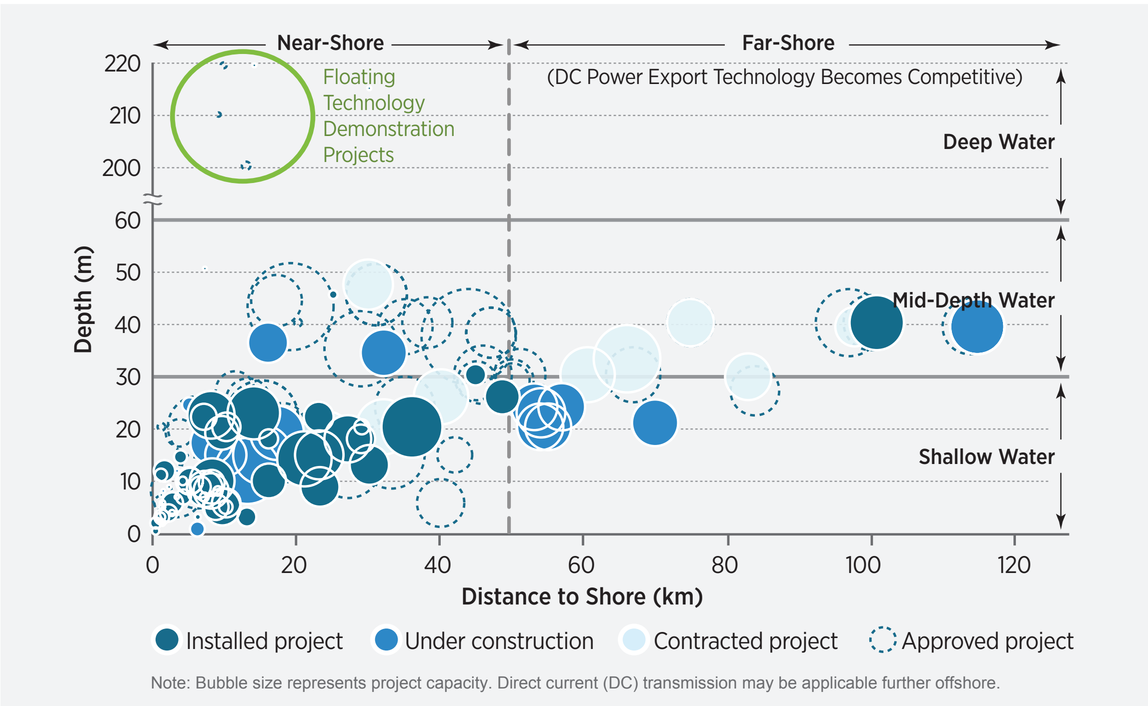
The continued rapid growth of offshore wind turbine capacity since 2008 has resulted in a commensurate growth in rotor diameter. These new offshore turbines comprise rotors up to 165 m in diameter, with blade lengths up to 80 m in length. Blades of this length challenge the 2013 state-of-the-art composite fabrication facilities and require special attention to ship blades to the project site. Blade designers have

51. The data in this figure and most data discussed in this section rely on data from deployed offshore turbines outside the U.S. since there are currently no utility-scale offshore wind projects operating in the U.S.



Source: National Renewable Energy Laboratory

Figure 2-32. Technology trends in offshore wind turbines, 2000–2016

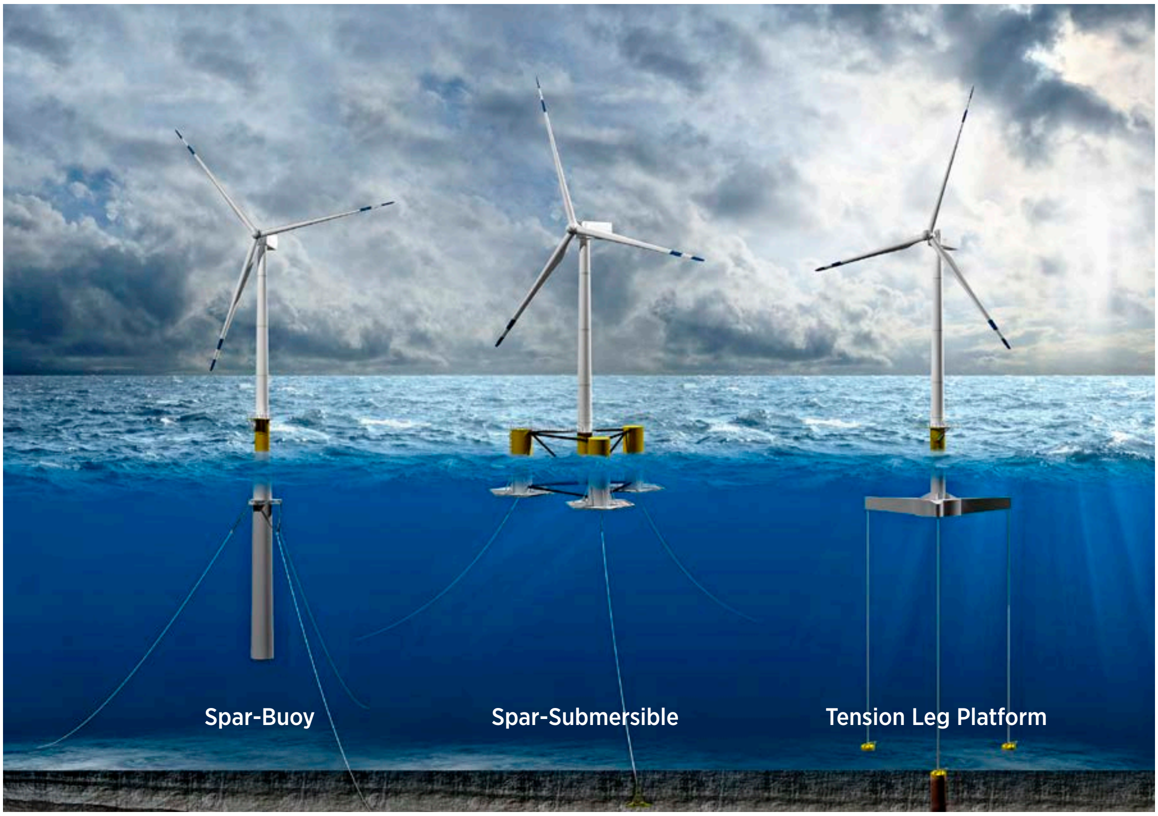


Source: National Renewable Energy Laboratory

Figure 2-33. Characteristics of offshore wind projects in Europe, 2013 increasingly moved to lighter weight materials such as industrial carbon fiber laminates, modular prepreg members, and automated fiber placement production technologies to achieve longer, stiffer blades. As of 2013, all utility-scale offshore wind turbines are designed to operate upwind of the tower, except for the Hitachi 2 MW downwind machine. There are several of these Hitachi units operating in Japan, including two floating turbines: one at Kabashima, Japan [120] and another deployed in phase 1 of the Fukushima Forward floating offshore wind project. Further development of larger machines may lead to more downwind turbine designs for offshore wind. Extreme blade lengths may deflect beyond practical upwind rotor limits, while low frequency noise concerns that restrict downwind turbines on land are less likely to be a factor in an offshore environment.

Water depth is a strong design driver in offshore wind technology development. In 2008, all installations were in shallow water less than 30 m deep, except for a 45-m deep demonstration project in the Beatrice fields off Scotland (developed by Talisman Energy). These installations were completed using conventional jack-up barge cranes on monopole or gravity-based substructures. In 2014, much of the development was mid-depth sites that are further from shore and require multi-pile substructures such as jackets and tripods. The costs increase as turbines are placed in deeper waters but conflicts with the environment and competing human use are likely to be lower [55]. Figure 2-33 shows the relationship between project depth, distance from shore, and project size over the life of the industry.

Some large-scale deployments in Europe aggregate the wind plant electrical distribution systems from multiple wind projects to facilitate efficient power delivery to shore. Some projects have implemented multi-point high-voltage direct current transmission systems for long-distance transmission of power to shore, a trend which may continue as larger facilities



Source: National Renewable Energy Laboratory. Illustration by Joshua Bauer, NREL.

Figure 2-34. Illustrations of three classes of floating wind turbine technology continue to be built further from shore. Electrical transmission backbones such as these have already been proposed in the United States in advance of offshore wind construction [121].

The trend toward deeper water has also created interest in floating wind technology (see Figure 2-34). In 2009, the first utility-scale floating wind turbine was deployed by Statoil off the coast of Norway. The turbine was named Hywind I and used a 2.3-MW Siemens turbine on a floating spar substructure. Other technology demonstration projects have since launched in Portugal [122], Japan [123], and in the first U.S. offshore wind turbine at the University of Maine [124]. Additional full-scale demonstration projects are also underway [125].

Although not yet commercially proven, floating technology could play a key role in offshore wind, especially in the United States where more than 60% of the offshore wind resource lies over water with depths of more than 60 m. In those areas, floating systems may have an economic advantage over fixed structures. The potential advantage is that floating systems at large production scale may be able to deliver lower system cost through efficiencies gained in mass production and the elimination of expensive at-sea construction steps. As of 2013, floating wind technology developers are demonstrating floating concepts with proven fixed-bottom offshore wind turbine designs.

Hurricanes pose a significant challenge to offshore wind turbines in areas where major tropical cyclone events regularly occur. This includes the U.S. Atlantic, Gulf of Mexico, and parts of the Pacific. In 2008, hurricane turbine ride-through designs were not yet being discussed, and the Minerals Management Service (now BOEM) was concerned about consistency and interpretation of the various standards [126, 127, 128]. Many developers were hesitant to consider hurricane-vulnerable sites as viable at all. As of 2014, hurricane-tolerant offshore wind design is discussed widely in international standards development organizations, with progress toward robust strategies. Turbine survivability under extreme ice loading has been demonstrated in the Baltic Sea, especially in Finland where ice conditions exceed extreme Great Lakes conditions on an annual basis [129]. These advancements in hurricane and ice load tolerance are important to expand developable opportunities for offshore wind.

2.5.6 Conclusions

Wind technology advancements, performance improvements, and cost reductions have exceeded levels viewed as aggressive in 2007 and 2008. Wind turbine technology continues to progress toward larger turbines with higher nameplate capacity, and industry is gaining increased understanding of ways to improve reliability. Manufacturers of offshore technology can leverage many of the same enhancements as in land-based wind technology, but there will also be unique design issues for offshore. Numerous actions and advancements in wind plant technology, performance, reliability, and safety are needed to continue recent trends and achieve the deployment levels in the *Wind Vision Study Scenario*. Section 4.2 discusses several *Wind Vision* roadmap actions regarding wind plant technology advancement, while Section 4.4 reviews the wind power performance, reliability, and safety roadmap actions.

Wind plant technology advancement actions in the *Wind Vision* roadmap include:

- Developing next-generation wind plant technology for rotors, controls, drive trains, towers, and offshore foundations for continued improvements in wind plant performance and scale-up of turbine technology;
- Updating design standards and certification processes using validated simulation tools to enable more flexibility in application and reduce overall costs;
- Developing and validating a comprehensive suite of engineering, simulation, and physics-based tools that enable the design, analysis and certification of advanced wind plants. Improving simulation tool accuracy, flexibility, and ability to handle innovative new concepts;
- Developing and sustaining world-class testing facilities to support industry needs and continued innovation; and
- Developing revolutionary wind power systems by investing R&D into high-risk, potentially high-reward technology innovations.

The *Wind Vision* roadmap addresses wind power performance, reliability, and safety with actions to:

- Increase reliability by reducing unplanned maintenance through better design and testing of components, and through the adoption of condition monitoring systems and maintenance;
- Develop a world-class database on wind plant operation under normal operating conditions by collecting wind turbine performance and reliability data from wind plants to improve energy production and reliability under normal operating conditions;
- Ensure reliable operation in severe operating environments by collecting data, developing testing methods, and improving standards;
- Develop and promote best practices in operations and maintenance strategies and procedures for safe, optimized operations at wind plants; and
- Develop aftermarket upgrades to existing wind plants and establish a body of knowledge and research on best practices for wind plant repowering and decommissioning.

2.6 Supply Chain, Manufacturing, and Logistics

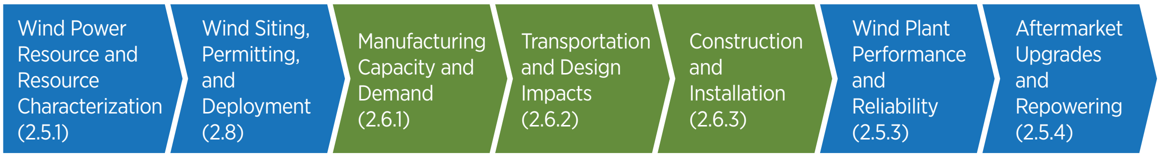


Figure 2-35. Elements of the U.S. wind power supply chain mapped to sections in this report

The U.S. wind industry supply chain comprises a range of companies spanning the life cycle of a wind plant, from initial resource assessments through long-term operation. The focus of this section is on the manufacturing, transportation, and construction portion of the supply chain, with other areas addressed throughout this report as indicated in Figure 2-35.

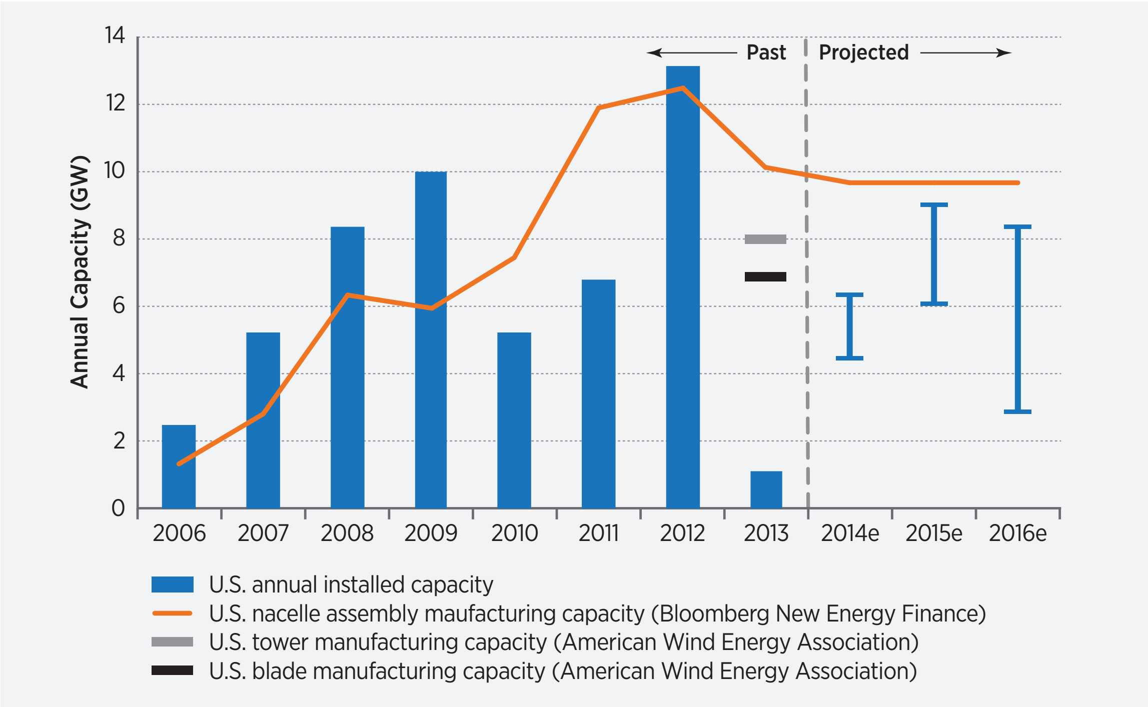
With historical domestic demand stability, wind manufacturing has moved toward higher U.S. domestic content. Unstable future demand may erode the domestic supply chain.

The U.S. manufacturing supply chain includes at least 560 companies, in more than 43 states, that process raw materials and manufacture and assemble wind turbine components [7]. The overall share of domestically manufactured turbines and components has increased over the last decade, leading to a decrease in share of imported wind turbines and select components despite record installations and industry growth [25]. Turbine technology has scaled up as well, increasing the size of components such as blades and towers, making transportation more costly and complex, and domestic manufacturing more likely. These trends helped support more than 80,700 domestic jobs across the supply chain by the end of 2012, including more than 25,500 in manufacturing (see Section 2.4.3 Workforce). With the market uncertainty created by the expiration of the PTC in 2013, employment in the U.S. wind industry contracted to 50,500 full-time equivalents across the supply chain—17,400 in the manufacturing sector—by the end of 2013 [7].

Manufacturing capacity and demand, including domestic content and international trade, raw materials, and repair and remanufacturing are summarized in 2.6.1. Section 2.6.2 covers the transportation logistics and design impacts, while Section 2.6.3 discusses installation issues.

2.6.1 Manufacturing Capacity and Demand

U.S. manufacturers have responded to the demand for wind power projects. In the five years leading up to 2013, the United States installed more than 43 GW of wind, leading to a cumulative installed capacity of more than 61 GW by the end of 2013 [9]. With the rapid increase in turbine installations, more original



Sources: Wiser and Bolinger [6], Bloomberg New Energy Finance; American Wind Energy Association

Figure 2-36. Domestic wind turbine nacelle assembly, blade, and tower manufacturing capacity vs. U.S. wind turbine installations

equipment manufacturers established regional offices, developed local supply chains, and expanded U.S.-based manufacturing and assembly capacity [25]. Figure 2-36 shows how domestic nacelle assembly and blade and tower manufacturing capability compare with both growth in wind installations and projections for future growth.

In addition to expanded nacelle assembly manufacturing capability, by the end of 2013, the U.S. domestic supply chain had the capacity to produce 10,000 blades (6.2 GW) and 4,300 towers (8 GW) annually [9]. This trend demonstrates the ability of the industry to invest in new domestic manufacturing capacity, which, in turn, can facilitate rapid increases in demand needed to support the deployments in the *Wind Vision Study Scenario*.

Due to the lack of near-term (~two years) demand—driven primarily by uncertainty about the extension of the PTC— only 1 GW of additional wind was installed in 2013. This represents a 92% drop in the market relative to 2012 [9]. Most, if not all, original equipment manufacturers and their suppliers scaled back capacity. In addition to the closure of five major wind-related manufacturing facilities and the exit of seven additional facilities during 2012, two major wind-related manufacturing facilities were shuttered during 2013 [7]. Further information on the domestic supply chain capacity can be found in Appendix E.

Domestic Content and International Trade

The wind industry supply chain has become increasingly globalized, with manufacturing locations based upon factors including national policies, labor costs, transportation costs, original equipment manufacturer supply chain strategies, and technology development. Component country of origin varies widely, depending upon the type of components. For example, larger components that are more costly to transport (i.e., blades and towers) are more likely to be manufactured in the domestic market.

Within the U.S. market, the overall share of domestically manufactured turbines and components has increased over the last decade, leading to a decrease in the share of imported wind turbines and select components despite record installations and industry growth. The combined import share of *selected* wind equipment tracked by trade codes (e.g., blades, towers, generators, gearboxes and complete nacelles), when presented as a fraction of total equipment-related turbine costs, declined from roughly 80% in 2006 and 2007 to 30% in 2012 and 2013 [6]. Domestic content for some large components, such as blades and towers, ranged between 50% and 80% in 2012–2013. The share of wind turbine project costs (including project costs for non-turbine equipment sourced domestically), was approximately 60% in 2012. Domestic content was considerably below these levels for generators and much of the other equipment internal to the nacelle, however, and much of this equipment is not tracked by trade codes [6].

National policies have also affected the global supply chain, which directly influences the percentage of imported vs. domestic content of some components. U.S. exports of wind-powered generating sets increased from $16 million in 2007 to $421 million in 2013, not including export of components that would add to the total export value (e.g., blades and towers) [6]. The two largest markets for U.S. exports between 2006 and 2013 were Canada (52%) and Brazil (33%) [6]. Policies that continue to drive local content requirements in Brazil, and until December 2013 in Canada as well, may limit U.S. exports to those markets. On the import side, China provided more than 50% of total imported towers to the United States in 2011 and 2012. In 2012, however, a trade dispute over low prices led the U.S. Commerce Department to levy large tariffs on imported towers from China. This could result in supply shifts, resulting in some additional domestic capacity and imports from countries not impacted by the tariffs [25]. Further details on the value of imports and exports can be found in Appendix E.

Raw Materials

One of the considerations in the *20% Wind Energy by 2030* report was the availability of raw materials to meet that scenario. Wind turbines are primarily constructed of abundantly available materials such as steel, glass, copper, and aluminum, so supply concerns are generally minimal. A supply chain analysis of wind technology commissioned by the International Energy Agency (IEA), however, identified two potential bottlenecks for highly critical materials: carbon fiber used in advanced rotor blades, and rare earth metals used for some permanent magnet generators [130]. While there have not been any fundamental raw material supply concerns for wind turbines, the trends in commodity material prices in the decade leading up to 2013 have had a significant impact on wind turbine prices and design choices. Analysis performed by LBNL estimated that commodity price changes accounted for nearly 12% of the overall general turbine price *increase* that occurred in the industry between 2002 and 2008, and nearly 35% of the price *decrease* from 2008 to 2010 [131]. More information on raw material trends can be found in Appendix E.

Repair and Remanufacturing

The market for repair, replacement, and repowering wind plants will continue to grow as installed assets of more than 61 GW of cumulative installed wind capacity age. While 52% of the installed U.S. wind turbine fleet was less than five years old in 2014, 34% of installed wind turbines were commissioned between 1982 and 2001 [132]. With O&M representing around 25% of lifetime turbine costs and levelized replacement costs representing 30% of O&M [28], there is a growing aftermarket for remanufactured and replacement components to support expansion for domestic manufacturers. Further details on repair and remanufacturing can be found in Appendix E.

2.6.2 Transportation and Design Impacts

The U.S. market has expanded to include lower wind speed sites (average wind speeds <7.5 m/s) closer to population centers. This is in part because of technological advancements and policy drivers. In some regions, it is also due to limited access to available transmission lines. As a result, from 1998 to 2013,

Turbines with larger blade and tower components can capture more wind at lower wind speed sites, but pose transportation and logistics challenges.

the average estimated quality of the wind resource at 80 m for newly installed wind projects dropped by approximately 10% [6]. This trend has increased the complexity and cost of transportation logistics because components such as blades and towers have increased in size to capture the resource at lower wind sites. As a result, existing transportation infrastructure is increasingly impacting component designs to balance energy production with transportability.

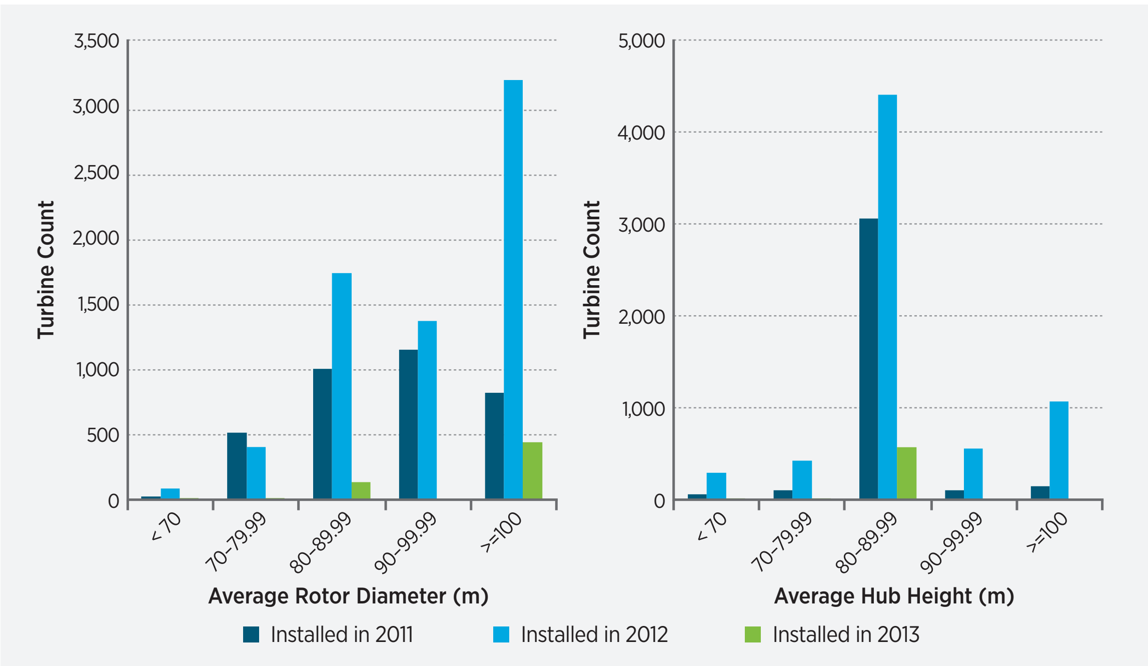
Transportation Logistics

Installed turbine power ratings have continued to rise, to an average of 1.95 MW in 2012 including multiple models at more than 2 MWs and above [53]. As OEMs seek to capture more wind at lower wind speed sites, average rotor diameters have increased rapidly. Tower components have also increased in size and weight to access better winds higher above the ground (Figure 2-37). Wind turbine blades longer than 53 m begin to present a transportation obstacle due to the large turning radius, which hinders right of way or encroachment areas within corners or curves on roads or railways (Figure 2-38). Tower sections are generally limited to 4.3 m in diameter, or 4.6 m where routes permit, to fit under overhead obstructions.

In addition to the physical limitations associated with wind components, each state along a transportation route has different requirements to obtain permits. This problem is exacerbated by higher volumes of shipments as wind turbine deployments increase. States are shifting the burden of proof for the safety of large, high-volume shipments to the wind industry. To address the increased complexity and resulting costs and delays associated with these logistics challenges, AWEA's Transportation and Logistics Working Group is coordinating with the American Association of State Highway and Transportation Officials to harmonize permitting processes across states. The increased size, mass, and quantity of wind components has resulted in more actively managed wind turbine transportation logistics, making use of a variety of land transportation methods and modes. This has resulted in increased project costs of up to 10% of capital costs for some projects [133]. Further details about trends in transportation logistics for wind projects can be found in Appendix E.

Design Impacts

Transportation constraints increasingly impact the design of wind turbine components, leading to higher capital costs resulting from suboptimal design. A prime example can be found in the industry-standard rolled steel wind turbine towers, which are limited to a structurally sub-optimal 4.3 m diameter to comply with size and weight limits of U.S. roads. While it is possible to construct towers with hub heights up to 160 m at this constrained diameter, this height results



Note: In 2013, only 1 GW of wind capacity was installed, largely driven by the PTC expiration in 2012.
Source: AWEA 2014 [9]

Figure 2-37. Rotor diameter and hub height trends of wind turbines, 2011–2013

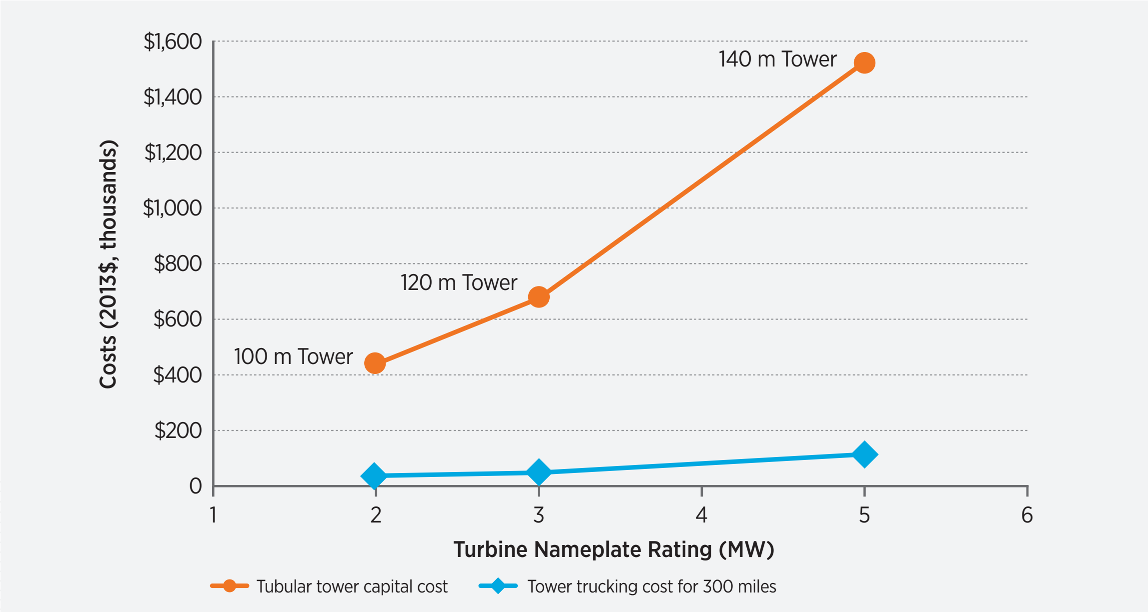
Source: SSP Technology

Figure 2-38. Example of wind turbine blades transportation obstacles

in an exponential increase in the mass and cost of rolled steel towers as plotted in Figure 2-39. Under transportation constraints as of 2014, tall towers are not economical in the sizes necessary to deploy wind in new, low and moderate wind speed land areas that are of interest to the industry to support cost reductions described in Section 2.1.3. It is important to note that these capital costs are substantially larger than the cost to transport the tower sections. Similar transportation-design tradeoffs impact blades with respect to other aspects such as maximum chord dimensions. Details about some proposed solutions for on-site manufacturing of towers to mitigate transportation constraints can be found in Appendix E.

2.6.3 Installation

Because of the lift height and mass, hoisting a wind turbine nacelle onto its tower requires the largest crane capacity of all wind turbine construction and installation phases. The masses of a 3-MW nacelle assembly and a 5-MW nacelle assembly are approximately 78 metric tonnes (t) and 130 t, respectively, without the gearbox and generator (104 t and 173 t with those components installed). Continued increases in tower heights and machine ratings are driving higher nacelle and blade weights. As a result, the availability, scheduling, and logistics of larger cranes have become increasingly challenging. Alleviating this challenge could influence future wind deployment by facilitating cost-effective development in more regions



Source: Cotrell [134]

Figure 2-39. Estimates of trucking and capital costs for conventional tubular towers, 2013

of the United States. Analysis performed by NREL indicates that having installation equipment capable of hoisting a 2.4-MW turbine onto a 140-m tower would increase the economically deployable area for wind by 614,000 km^2 (237,000 mi^2), especially in the southeastern United States [134]. Further details can be found in Appendix E, Section E.6.

Because mobile cranes capable of installing the majority of turbines deployed in the United States are of a common size used for construction and other industries, an ample supply of such cranes existed into 2014. As the number of turbines installed at 100 m hub heights and above has increased, however, concerns about the availability of larger capacity cranes has grown. Table 2-6 shows the sharp drop in available U.S. cranes when shifting from the standard 600-ton to the 1,250–1,600-ton class cranes needed for taller towers and heavier nacelles.

Another challenge with larger crane classes is difficulty transporting them to and maneuvering them within the wind plant, especially in complex terrain. A 1,600-ton crane has a width of nearly 13 m (41 feet), wider than a two-lane interstate highway (including shoulders), and requires more than 100 semi-tractor trailers to transport it between projects. This makes transportation between turbines difficult and costly. Further details on construction equipment trends can be found in Appendix E.

Table 2-6. Crawler Crane Availability in 2013 Relative to Wind Turbine Hub Heights

Crawler Crane Class	Approximate Number of Cranes in United States	Applicable Turbine Sizes
600 metric tonnes	85	3 MW/140 meter hub height
1,250–1,600 metric tonnes	10	5 MW/150 meter hub height 3 MW/160 meter hub height

Source: Cotrell [134]

2.6.4 Conclusions

Based on installation experience from 2006 to 2013, expanded domestic manufacturing to reach deployment levels of the *Wind Vision Study Scenario* for 2020 and 2030 will not be constrained by raw materials availability or manufacturing capacity. With recent domestic demand stability, wind manufacturing has moved toward higher domestic content. Past experience indicates unstable demand may drive reductions in domestic content and potentially shift equipment production overseas. Dips in demand have directed resources to other industries and could slow the return to high levels of deployment. Continued innovation in turbine design, manufacturing, transportation, and construction will be needed to overcome logistical barriers, reduce wind turbine cost, and improve international competitiveness. To capture more wind at lower wind speed sites, turbines with larger blade and tower components pose additional challenges for transportation logistics.

Section 4.3 discusses several *Wind Vision* roadmap actions regarding supply chain, manufacturing, and logistics including: increasing domestic manufacturing competitiveness with investments in advanced manufacturing and research into innovative materials; developing transportation, construction and installation solutions for deployment of next-generation, larger wind turbines; and establishing domestic offshore manufacturing, supply chain and port infrastructure.

2.7 Wind Integration and Delivery

Wind power has become a major source of electricity supply in the United States and around the world. Experience with the transmission, integration, and delivery of this electricity has verified the conclusions of numerous integration studies: No technical limits or obstacles have been identified that would prevent wind-generated electricity from meeting even greater portions of electricity demand in the United States. There may be a need for institutional or operational practice to change in some areas, however, so that wind power can be integrated successfully at increasing penetrations.[52]

Wind turbine technology has evolved to incorporate more grid-friendly features. System balancing could be a concern at higher penetrations. Reforms in many market areas with robust energy markets (e.g., PJM Interconnection, Midcontinent Independent System Operator [MISO]), along with market evolution in areas such as the Southwest Power Pool and the emerging Energy Imbalance Market, have improved the tools available to the system operator to manage the increased variability and uncertainty of wind power. Some areas now incorporate wind power into the economic dispatch process.[53]

The electric power network operates reliably with high wind contributions (10% and higher) today, with minimal impacts on network operating costs.

In regions with wind power contributions up to 20% of annual electrical demand in 2013, electric power systems operated reliably without added storage and with little or no increase in generation reserves [7]. Wind has also been proven to increase system reliability during some severe weather events. For example, in February 2011, cold weather disabled 152 power plants in Texas, mostly coal and natural gas. Wind generation produced approximately 3,500 MW of output during this event, helping to avoid outages [135]. Experience with wind generation confirms that opportunities exist to increase grid operating efficiency and reduce costs by increasing flexibility.[54]

Wind power has characteristics that differ from generation powered by nuclear, gas, and coal.[55] Because wind generation is driven by meteorological processes, it is intrinsically variable, from real-time, minute-to-minute fluctuations to yearly variations affecting long-term planning for utility operations.

52. The Intergovernmental Panel on Climate Change report on wind energy [85] provides a heavily referenced section summarizing the potential integration challenges of large amounts of wind.

53. See for example MISO 2013 Annual Market Assessment Report, available at *https://www.misoenergy.org/Pages/Home.aspx#*.

54. Flexibility is the ability of the power system to respond to variations in supply and/or demand.

55.. Solar energy has similar characteristics to wind power and can complement wind power with respect to the diurnal pattern of generation.

These characteristics can require changes in system operational practices and the potential addition of flexibility reserves to help manage increased variability and uncertainty from wind power.[56] Grid operators that have adapted operating practices, such as ERCOT and MISO, have seen integration costs and impacts that are less than predicted by many studies. Both ERCOT and MISO incorporate wind power plants into the economic dispatch, which results in more cost-effective operation of the power system. ERCOT provides an example of very low integration costs—approximately $0.50/MWh of delivered wind power. The only source of increased cost ERCOT could identify was a small increase in operating reserve requirements [136].

In the United States, studies to analyze the impact of wind power on planning and operation of power systems were performed *before* significant levels of wind were installed. As wind turbines and wind power plants were developed, the findings of the initial wind integration studies were confirmed: Large amounts of wind power can be reliably integrated, and even larger amounts can be integrated with cost-effective changes to grid operating procedures and added transmission capacity. The following discusses the studies as well as actual operating practice, which demonstrates how study results were confirmed by actual experience.[57]

In addition to studies described in this section that simulate operational characteristics of large amounts of wind power, significant levels of wind have also had an impact on the desired characteristics of other resources (generation, demand response, or storage) needed to complement wind power. For example, wind power provides limited contribution to planning reserves, often called "capacity value" [137]. As the wind penetration rate increases, at some point there will likely be a decline in per-unit capacity value of wind generation. This decline will depend on the geographic dispersion and statistical correlation of wind plant output levels across large regions, and will likely be moderate at correspondingly low-to-moderate penetration rates. The effect on overall electricity cost will depend on a number of items, including future carbon values, conventional fuel costs, and the cost of new flexible technologies that may include some combination of fast-response thermal or hydropower generation, along with demand response and electricity storage.

Section 2.7.1 summarizes some recently completed studies on wind integration, while Section 2.7.2 summarizes operational experience and highlights how large amounts of wind power can be reliably integrated into the power system. Flexibility, which is important for easily integrating wind into the power system, is discussed in Section 2.7.3. Transmission system capacity issues are addressed in Section 2.7.4. Section 2.7.5 discusses how industry organizations are addressing wind integration into the power system.

2.7.1 Wind Integration Studies

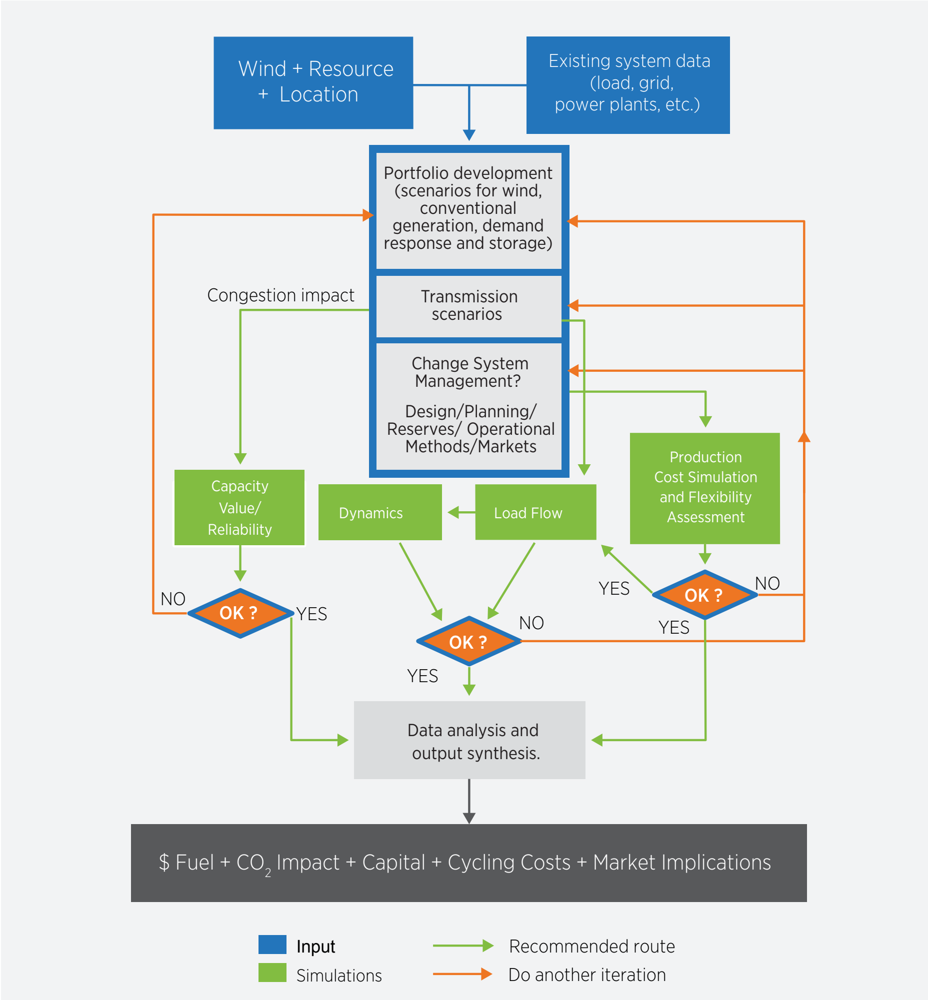
Large amounts of wind power have already been reliably integrated into the power system [25]. Numerous in-depth wind integration studies have confirmed that amounts of wind power far larger than the 2013 national average of 4.5% of end-use demand can be added to the power system without harming its reliability [138, 139]. Wind integration does not come without costs and impacts, however, including power system balancing and scheduling flexibility. It should be noted, though, that the addition of any type of generation will likely impose an integration cost and impact.[58] Many studies conducted in Europe and the United States indicate that wind power contributions up to and above 20% are technically possible, but with rising integration costs. These cost calculations are complex and specific to system and region [140]. A range of studies have quantified these balancing costs as roughly $1.40 to $5.60/MWh of wind power generated, generally increasing with wind power penetration, whereas the cost of wind power typically ranges from $30-60/MWh [141].

In order to understand the impacts of wind, utilities and transmission system operators have conducted integration studies of electric power system operation and planning that include low (a few percent) to high

56. Reserve generating capacity is equipment that is ready to add power to the grid to compensate for increased load or reduced generation from other units.

57. For more detailed discussion about wind power integration, see : *Review and Status of Wind Integration and Transmission in the United States: Key Issues and Lessons Learned* NREL TP-5D00-61911 [140].

58. See, for example, Milligan, M.; Ela, E.; Hodge, B.; Kirby, B.; Lew, D.; Clark, C.; DeCesaro, J.; Lynn, K. (2011). Integration of Variable Generation, Cost-Causation, and Integration Costs. Electricity Journal. Vol. 24(9), November; pp. 51-63. Available at http://dx.doi.org/10.1016/j.tej.2011.10.011



Source: IEA Wind [142]

Figure 2-40. Flowchart of a full wind integration study

(in excess of 20% of annual electricity consumption[59]) contributions of electricity from wind power. The basic methodology for carrying out a wind integration study has advanced significantly since the early 2000s. Originally, evaluations of wind power's impact on operations treated the technology as an incremental addition to an otherwise unchanged conventional power system. Studies prior to 2008 attempted to estimate the hypothetical cost of operating a power system with wind power compared to some other power source that is perfectly predictable and controllable. Most of those early studies estimated the resulting costs at up to $5/MWh of wind power [25].[60]

By 2013, integration studies had progressed to consider wind power as a fully integrated part of the generation fleet. Integration studies include the recognition that all generation sources have integration costs and that individual loads also have variability and uncertainty. More recent studies (after about

59. Wind power that provides an annual 20% share of consumption will, at times, have high instantaneous shares of electricity. See, for example, Lew et al., Western Wind and Solar Integration Study Phase 2. *http://www.nrel.gov*

60. A few studies found cost impacts up to $12/MWh. These studies examined relatively small balancing areas with limited electricity transfer capability to and from neighboring regions, and, in some cases, did not accurately represent the impact on power system operations. As discussed later in the section, these characteristics pose challenges for wind integration.

2010) capture not only the impacts of wind on system operation, but also the overall cost and emissions savings due to displaced thermal generation. Integration studies have evolved toward a comprehensive process that compares reliability impacts and overall system operating costs for alternative configurations of generators to serve system load [142]. This process is summarized in Figure 2-40. Although this figure is designed to show how integration studies should be performed, it also illustrates the relationship between various integration aspects that need to be evaluated when increasing levels of wind power are introduced into the power system. Although actual assessments of installed wind power impacts may not be performed in a systematic way, all of the elements below need to be successfully managed if wind power is to be effectively integrated into the power system.

Integration studies are important tools to help quantify the value of alternative approaches to adding increased amounts of wind to conventional generation and load management. Many wind integration experts now recognize that it is difficult—if not impossible— to separate wind integration costs from other impacts on the power system, e.g., displacing other generation. As a result, the focus of wind integration studies has shifted to broader evaluations of power system economics.

2.7.2 Operational Experience

Wind generation contributed 4.5% of U.S. net electric power sector demand in 2013 [82]. In that year, wind power in South Dakota and Iowa generated an amount equal to more than 20% of each state's overall electric energy consumption. In Colorado, instantaneous contributions from wind up to 60% were successfully managed by the power system operator [9]. Figure 2-41 shows recent high-wind penetration events in the United States. In all of these examples, the electric power system continued to operate reliably.

Other countries are using even higher shares of wind power to meet electricity needs. Denmark leads in wind generation, obtaining 32.7% of its electricity from wind in 2013, followed by Portugal (23.5%), Spain (20.9%), Ireland (16.3%), and Germany (8.9%) [143]. Instantaneous contributions of 93% were recorded in Portugal and 50% in Ireland in 2012 [142]. This experience by grid operators facilitates better understanding of the impacts of wind on the power system, as well as opportunities to take advantage of wind power's benefits and minimize its costs.

Operational experience has confirmed the findings of wind integration studies: large amounts of wind power can be reliably integrated into the power system. Experience also supports the conclusion that efficient grid operating procedures such as large or coordinated balancing areas,[61] fast-interval generation scheduling and dispatch,[62] setting wind generator schedules as close as possible to the dispatch time to minimize forecast errors, and the use of wind power forecasting can greatly facilitate wind integration and reduce costs.

Most North American power markets now integrate wind power into their security-constrained unit commitment[63] and security-constrained economic dispatch[64] process, allowing the dispatch of wind plants along with conventional power plants based on current grid conditions and economics. This effectively gets wind into the real-time economic optimization process for running the power system, and in turn, encourages the participation of wind plants in the day-ahead markets. Security-constrained economic dispatch also makes wind dispatchable and economical, allowing some degree of wind-plant output control by the system operator.[65] This allows wind forecasts to become more useful and valuable to wind plant operators, market participants, and system operators, because wind is better integrated into systems and markets.

61. A balancing area is a predefined area within an interconnected transmission grid where a utility, an independent system operator, or a transmission system operator must balance load (electrical demand) and electrical generation while maintaining system reliability and continuing interchanges with adjoining balancing areas. An interconnected grid can have one or many balancing areas. For example, the Western Interconnection, which covers much of the western U.S. and western Canada, has 35 balancing areas, while the Texas Interconnection has only one.

62. Dispatch is the real-time centralized control of the on-line generation fleet to reliably and economically serve net system load.

63. Unit commitment is the process of starting and synchronizing power plants to the grid to minimize operating cost and maintain power system reliability.

64. Economic dispatch is the process of altering the output of one or more generators on an economic basis.

65. Wind plant output can be ramped down easily; ramping up is possible only if the plant is operating below the maximum level allowed by current wind conditions.

In 2013, grid operators with extensive experience using wind on their systems concluded the need for additional operating reserves associated with wind are low.[66] ERCOT calculated that the incremental reserve needs for about 10 GW of wind on its system translated into a dollar value addition of $0.50/MWh of wind, or about 6¢/month on a typical Texas household's $140 monthly electric bill.[67] Similarly, MISO, which serves the U.S. Midwest and Manitoba, Canada, has described more than 12 GW of wind generation as having little to no effect on its reserve needs [144].

Energy markets react to and compensate for variability and uncertainty in the aggregate wind and load. ERCOT and MISO, both with approximately 9% of annual generation coming from wind power, have been able to integrate large amounts of wind with minimal increases in reserve needs because they employ day-ahead, hour-ahead, and 5-minute energy markets. These system operators also incorporate wind power into power system dispatch [145] by setting the output schedule for wind energy based on the wind output level 10 minutes before real-time, reducing the frequency and magnitude of forecasting error.

Other initiatives have resulted in intra-hour scheduling or dispatch. For example, the Federal Energy Regulatory Commission's (FERC's) Order 764 (Integration of Variable Energy Resources) required public utility transmission providers to allow transmission customers to schedule at 15-minute intervals. Bonneville Power Administration implemented a successful intra-hour scheduling pilot in 2011 that is now a formal business practice.

Unlike ERCOT and MISO, operators in much of the western United States use hourly energy schedules and set the wind power output based on wind output an hour or more before real-time. During these longer intervals, wind power output can change significantly. Shorter (5-minute) scheduling and dispatch would significantly improve the ability of the power system to effectively integrate large amounts of wind power, whereas the current hourly scheduling practice increases reserve requirements. In late 2014, an Energy Imbalance Market began operating within the California Independent System Operator and PacifiCorp operating regions, using a security-constrained economic dispatch at 5-minute time steps. NV Energy will likely join this market in 2015, and the Northwest Power Pool is undertaking the analysis of a similar security-constrained economic dispatch for the Northwest.

More accurate wind forecasting has helped to reduce system operating challenges from unexpected wind plant outputs in all time frames. Forecasts are particularly important in the day-ahead, hours-ahead, and minutes-ahead time frames for scheduling wind generation into power systems and markets. Developments in wind power forecasting have also reduced the integration challenges associated with variable generation technologies [146, 147, 148]. By 2014, most parties were comfortable with making the system operator's forecasts publicly available in some form, and then combining those results with additional forecasts and information from market participants.

Grid-friendly features that have evolved include low-voltage ride-through, which allows wind turbines to stay online during low-voltage events, thus contributing to system stability. In addition, frequency response—the ability of the wind turbine to increase or decrease generation to help support nominal system frequency of 60 Hertz—is a feature of modern wind turbines. The ability to respond to automatic generator control signals allows wind turbines to provide regulation service, which is system balancing on very short time scales—from about 4 seconds to several minutes, depending on the region. Finally, simulated inertial response provides fast response during a disturbance. With the potential retirement of large coal generators during the next several years, system inertia will decline. This is attracting significant attention in the power system community, which

66. Operating reserves are generating equipment that is ready to add power to the grid and demand response that is ready to reduce consumption to compensate for increased load or reduced generation from other units (such as wind, or solar, and conventional power plants).

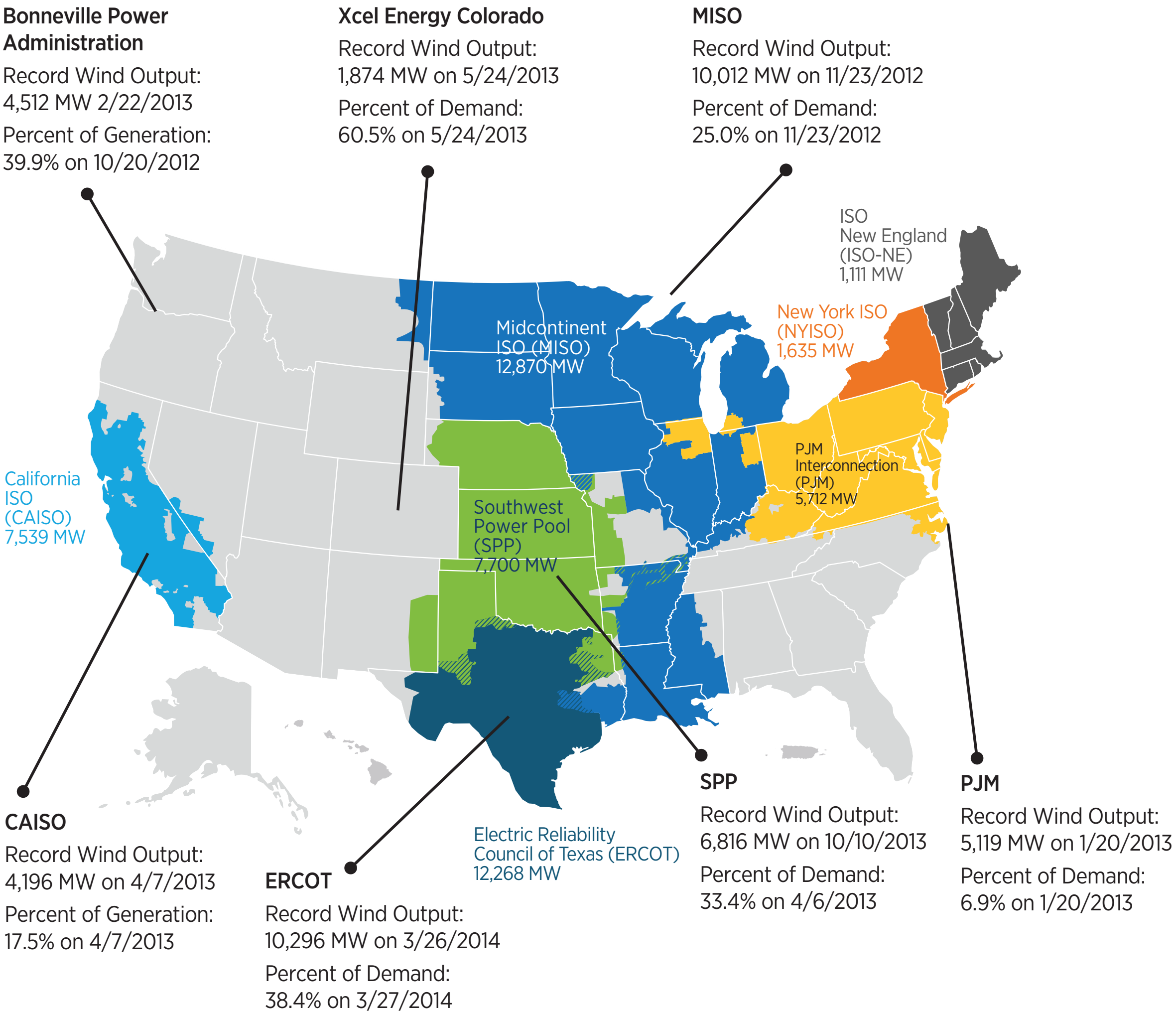
67. Based on a calculated wind integration cost of $0.50 per MWh of wind power, which equals $.046 per MWh of total load served in ERCOT at 9.2% wind power use (*http://uvig.org/events/#!/5701/2013-forecasting-workshop-2*), multiplied by the 1.262 MWh used per month by the average Texas household (Table 5a at *http://www.eia.gov/electricity/sales_revenue_price/*).

to date has not performed rigorous analysis of how simulated inertial response from wind turbines in the face of significant coal retirements will impact system stability. Such studies will likely gain momentum.[68]

Over the past few years, wind plants have been instrumental in maintaining reliable system operation during market changes and weather events. Text Box 2-7 describes wind's contributions during some of these events.

2.7.3 Flexibility

Flexibility is important for easily integrating wind and can come from changes to grid operating practices, changes in market design, or physical changes to power system resources. Power systems operating successfully with large wind contributions have adequate levels of flexibility that facilitate variable generation. Flexible power systems have some or all of the following characteristics:



Note: Acronyms used in graphic: Midcontinent ISO (MISO); PJM Interconnection (PJM); Southwest Power Pool (SPP); Electric Reliability Council of Texas (ERCOT); California ISO (CAISO); Independent system operator (ISO) .

Source: AWEA [7]

Figure 2-41. Key grid operating areas experiencing high instantaneous contributions from wind, 2012–2013

68. See NREL Western Wind and Solar Integration Study *http://www.nrel.gov/electricity/transmission/western_wind.html and* Active Power Control project *http://www.nrel.gov/electricity/transmission/active_power.html*) for more information.

Text Box 2-7.

Utility Wind Management

- While wind power output changes with the wind speed, such changes occur far more slowly than the unexpected outages that can occur at large conventional power plants.
- Wind power output is predictable using weather forecasting, and the technology can often be used to fill demand when conventional power plants fail.
- Long-term PPAs for wind power provide a buffer against price increases for other fuels.
- In Nebraska, as natural gas prices surged because of demand in the winter of 2013, 300 MW of wind provided 13% of demand and kept prices down. The utility shut down natural gas generation because prices were up more than 300%.
- Across New England, high output from the region's wind plants moderated the effect of high natural gas prices in 2013.

- Frequent and short dispatch and scheduling intervals with a look-ahead function to allow full access to physical flexibility of the resource (generation, demand response, and storage);
- Operating responsibilities shared over large geographic areas to allow access to a large fleet of power plants for energy generation and reserves;
- Connectivity[69] through the electrical transmission infrastructure that allows regional sharing, provides access to distant available generation of all types including wind, and allows averaging of non-coincident wind generation outputs from different locations;
- Demand-side management to help maintain the balance between generation and demand;
- Generators or cost-effective energy storage designed for rapid ramping of output levels, wide operating ranges, and short start-up times; and
- Appropriate operating procedures to access elements of flexibility.

Figure 2-42 illustrates many of the system flexibility elements discussed in this section and indicates the degree to which various types of power systems exhibit these elements. The most flexible institutional framework today appears to be a large regional transmission organization with spot markets and sub-hourly markets (represented in the figure with a green box with 10). Such a framework would encourage flexibility attributes needed for power system operation. The least flexible institutional framework is a small, vertically integrated local utility with a small balancing area and no sub-hourly markets or systematic sub-hourly economic dispatch.

ERCOT, MISO, and other operators with large amounts of wind power have grid operating responsibilities over large geographic areas (Figure 2-42). Aggregate wind power variability is reduced by averaging over large areas when weather patterns move across an area that has many wind projects. Large balancing areas also include more diverse generators and sources of demand response. Centralized energy markets with fast generator dispatch and robust ancillary services[70] markets make these power systems more flexible.

State-of-the-art wind plants with advanced controls can actually provide increased flexibility to the system. These plants can help the grid by providing grid services such as reactive power even when wind is not blowing [150], synthetic inertia, governor response, and regulation service, if proper incentives are provided.[71] The ability for wind generation to be dispatched below maximum power wind conditions

69. Connectivity is the ability to transfer electrical energy from one location to another through transmission lines and related infrastructure.

70. Ancillary services refer to the ability to respond quickly to changing system conditions, at any season or hour, when human operators or computers give the order. This process ensures demand-generation balance, system reliability and stability, and voltage support.

71. Synthetic inertia, governor response, and regulation refer to control of wind generator output in time frames ranging from cycles to seconds to emulate the response provided by conventional generators.

Accommodating Wind Integration

Example Utility Structures	Large balancing area	Geographically dispersed wind and solar	Wind forecasting effectively integrated into system operations	Sub-hourly energy markets	Fast access to neighboring markets	Non-spinning and 30-minute reserves for wind event response	Regional transmission planning for economics and reliability	Robust electrical grid	More flexible transmission service	Flexibility in generation	Responsive load	Overall
Large regional transmission organization with spot markets	10	8	7	10	7	2	7	6	7	7	3	7
Smaller independent system operator	6	6	6	3	3	2	6	4	7	2	2	4
Interior west and upper Midwest (non-MISO)	1	3	2	1	2	1	2	3	2	2	2	2
Large vertically-integrated utility	7	6	6	2	2	2	5	4	2	5	2	4
Smaller vertically-integrated local utility	1	3	2	1	2	1	2	4	2	2	2	2
Unconstrained hydro system										8		
Heavily fish-constrained hydro system										3		

Note: System flexibility increases as the color of the numbered boxes progresses from red to green, and as the number increases from 1 to 10. The items at the top of the table are those attributes that help efficiently integrate wind power into power systems operation. Although the table uses a simplistic 1–10 scoring system, it has proven useful as a high-level, qualitative tool. The red, yellow, and green result cells show the ease (green) or difficulty (red) that a hypothetical system would likely have integrating large amounts of wind power. RTO is regional transmission organization; ISO is independent system operator.

Source: Milligan [149]

Figure 2-42. Characteristics that help facilitate wind power integration

means wind power can provide fast and accurate response, which can be economically attractive when other options are limited. As with other ancillary services and providers, the necessary incentives must be in place to encourage this flexibility. NREL is conducting research on wind turbine active power controls along with market incentives necessary to induce the provision of these services when they are cost effective.[72]

2.7.4 Transmission System Capacity

Transmission is essential for bringing new wind capacity online and accessing the highest-quality, lowest-cost wind resources. Depending on its location and other factors, a land-based wind plant may require new transmission lines or increased capacity on existing lines. Grid-connected distributed wind

72. See NREL's *Active Power Controls* Web page at *www.nrel.gov/electricity/transmission/active_power.html*

projects might not require new transmission or distribution lines because distributed wind systems can effectively use available capacity on existing local distribution grids or are connected directly to an existing electrical service for a home, farm, or other facility.

Many sites with the nation's best wind power resources have minimal or no access to electrical transmission facilities.

Some of the nation's best wind resource regions are not accessible because transmission to these often rural regions may not exist.[73] Designing and building transmission does not present technical difficulties; however, siting the new lines and allocating the cost are both contentious topics (with or without wind) and there is currently a limited framework to resolve these issues. Broad allocation of transmission cost and proactive planning for transmission and siting are important to stimulate investment in new transmission capacity.

Wind power deployment has focused on the Great Plains region due to high average wind speeds and vast tracts of open land. Due to a lack of transmission and the long distance to load centers, however, the U.S. Interior continues to have substantial untapped resources. In 2013, a lack of transmission was listed as the primary siting-related constraint to expanded deployment [151]. In some regions, such as the Columbia Gorge in the Pacific Northwest, a significant amount of wind power can be developed close to existing transmission. There may be times that the transmission system is congested, resulting in the

Text Box 2-8.

Competitive Renewable Energy Zones in Texas

In the mid-2000s, wind generation in parts of Texas was being regularly curtailed when generation exceeded the capacity of the transmission lines. At the same time, wind development was being encouraged by the state's RPS, but developers were finding that many of the best areas for wind generation had little or no available transmission capacity. Installation of wind turbines continued, but in lower wind speed areas. Developers focused on available transmission capacity as the primary consideration.

In 2005, the Texas Legislature passed a law that required the Public Utility Commission of Texas to designate one or more Competitive Renewable Energy Zones (CREZ) and to approve transmission improvements to connect these zones with load centers in the ERCOT region. This solved the chicken-and-egg issue by determining that the transmission should come in advance of the wind (or solar) development for the good resource zones. Five zones and a CREZ transmission plan were approved in 2008.

The completed circuits of the Texas transmission plan relieve constraints on existing wind generation. Before the CREZ plan, existing and planned wind generation of 6,900 MW was located in the region and curtailment reached 17% of potential wind generation in 2009 (Table 2-7). By 2012, curtailment was down to 3.8%, falling to 1.2% in 2013, and, by 2014, 10,970 MW of wind generation was operating in ERCOT.

The new CREZ transmission has provided connection between wind resources in the Texas Panhandle (home to some of the best wind resources in the country) and the ERCOT market. As a result, wind developers have shown significant interest in the area. According to ERCOT, by early 2014, interconnection agreements had been signed for proposed projects totaling 6,947 MW, and applications for connection had been made for another 24,000 MW. The response was so overwhelming that the grid operator was already exploring additional Panhandle transmission expansions shortly after the CREZ was completed [7].

73. See, for example, American Transmission Company, *http://www.atcllc.com/learning-center/delivering-renewable-energy/*.

Table 2-7. Estimated Wind Curtailment by Area in GWh (and as a Percentage of Potential Wind Generation)

	2007	2008	2009	2010	2011	2012	2013
ERCOT	109 (1.2%)	1,417 (8.4%)	3,872 (17.1%)	2,067 (7.7%)	2,622 (8.5%)	1,175 (3.8%)	363 (1.2%)
Southwestern Public Service Company	N/A	0 (0.0%)	0 (0.0%)	0.9 (0.0%)	0.5 (0.0%)	N/A	N/A
Public Service Company of Colorado	N/A	2 (0.1%)	19 (0.6%)	82 (2.2%)	64 (1.4%)	115[a] (2.0%)	112[a] (1.7%)
Northern States Power Company	N/A	25 (0.9%)	42 (1.7%)	44 (1.7%)	59 (1.6%)	125 (3.0%)	284 (5.9%)
MISO, less Northern States Power Company	N/A	N/A	250 (2.0%)	780 (4.2%)	792 (3.4%)	724 (2.5%)	1,470 (4.6%)
Bonneville Power Administration	N/A	N/A	N/A	5[b] (0.1%)	129[b] (1.4%)	71[b] (0.7%)	6[b] (0.1%)
New York Independent System Operator	N/A	N/A	N/A	N/A	N/A	9 (0.3%)	50 (1.4%)
PJM Interconnection	N/A	N/A	N/A	N/A	N/A	125[c] (2.0%)	284 (1.9%)

a. Xcel Energy declined to provide 2012 and 2013 curtailment data for its Southwest Public Service and Public Service Company of Colorado service territories; Public Service Company of Colorado 2012/2013 data are estimated from Bird et al. (2014) [153].

b. A portion of Bonneville Power Administration's curtailment is estimated assuming that each curtailment event lasts for half of the maximum possible hour for each event.

c. 2012 curtailment numbers for PJM are for June through December only (data for January through May 2012 are not available).

Source: Wiser and Bolinger [6]

curtailment (manual or other reduction in wind power output) of wind power.[74] In other places, a trade-off exists between investing in new transmission to reach better wind resource areas and developing less-windy locations near existing transmission.

Transmission line planning criteria often dictate that new transmission capacity will not be built in advance of need, and wind developers are not willing to start projects if they have to wait five years—or in some cases longer—for new transmission to be completed. This so-called "chicken-and-egg" problem has been addressed in Texas using a model that could apply in other areas (see Text Box 2-8).[75]

Meanwhile, progress has been achieved nationally on overcoming transmission barriers, and curtailment of wind plants has been reduced from its 2009 peak. Since 2008, the United States has installed more than 2,300 circuit miles of new transmission lines annually. An additional 18,700 total circuit miles are planned for 2014 through 2019. In 2012, AWEA identified 19 near-term transmission projects that—if all are completed—could carry almost 70 GW of wind power capacity [154]. MISO has undertaken "multi-valued" projects, proposing and constructing transmission network upgrades that provide lower-cost energy [155]. FERC Order 1000[76] was affirmed in August 2014. The Order requires public utility transmission

74. Curtailment may be part of market operations in an RTO/ISO setting, in which wind plants bid their minimum running price. In non-RTO areas, or RTO regions that have not implemented economic dispatch for wind power, the specific mechanism for curtailment varies.

75. More details regarding this plan are available in the report: CREZ Transmission Optimization Study, *http://www.ercot.com/search/results?q=CREZ+Transmission+Optimization+Study* [152].

76. See *www.ferc.gov/industries/electric/indus-act/trans-plan.asp* for details.

providers to improve intra- and inter-regional transmission planning processes and to determine cost-allocation methodologies for new transmission plants. States, grid operators, utilities, regional organizations, and DOE also continue to take proactive steps to encourage transmission investment. Despite this progress, siting, planning, and cost-allocation issues remain key barriers to transmission investment, and wind curtailment continues to be a problem in some areas, mainly as a result of constrained transmission.

2.7.5 Industry Organizations are Addressing Wind Integration

Engagement by the power system industry is necessary to achieve the reliable integration of large amounts of wind power. The following discussion of organizations addressing integration is not exhaustive, but is intended to illustrate some of the key institutional involvement that has had an effect on wind integration.

Utility Variable-Generation Integration Group

The Utility Variable-Generation Integration Group (UVIG), previously known as the Utility Wind Integration Group, was established in 1989 as a forum for the critical analysis of wind and solar technology for utility applications. UVIG is a member-based organization made up of investor-owned utilities, public power providers, electric cooperatives, independent system operators, and other non-utility firms engaged in the wind and solar business. The organization provides credible information on the status of wind and solar technology, deployment and power-system integration [156]. It also encourages utility-to-utility dialogue on many of the integration and operational challenges of adding variable generation to the power generation portfolio in locations worldwide. UVIG has more than 160 members from the United States, Canada, Europe, Asia, and New Zealand.

North American Electric Reliability Corporation

Anticipating substantial growth of variable generation, the North American Electric Reliability Corporation's (NERC's) Planning and Operating Committees created the Integration of Variable Generation Task Force (IVGTF).[77] The task force is executing a three-phase approach to assess potential reliability impacts of wind and solar generation on the electric power system, and to recommend actions for NERC to implement [137]. NERC utilized technical experts from throughout the electric power industry to develop broad-based consensus documents as work products from this effort. The IVGTF effort is an ongoing process that incorporates continued operating experience and reflects advances in equipment and analysis tools. Some of this work is being transitioned to the Essential Reliability Services Task Force (ERSTF). As this work moves forward, the various task forces will evaluate whether changes are needed to NERC reliability standards or recommended practices, and the outcome could have a large impact on how much wind power can be added to the power system.[78] Dynamic stability studies are needed to ensure reliable operation of high wind power penetrations—some of these are underway and will be completed by early 2015.

Federal Energy Regulatory Commission

FERC's purview is the regulation of interstate power and energy transfers and markets, and the reliability of the bulk power system. A number of FERC actions have spurred the development of bulk power markets, and resulted in the formation of independent system operators and regional transmission organizations in the United States. Many of these actions were not specific to wind or other variable renewable energy sources, but they provided the framework for fundamental changes in bulk power market structures that increase the economic efficiency of operation, with or without wind power. In December 2005, FERC issued Order 661-A, which specified rules for low-voltage ride-through for wind turbines. Other FERC orders spurred more transparency in transmission service and promulgated regional transmission planning. Order 764, issued in June 2012, required transmission operators to offer 15-minute interchange scheduling, mandated the use of wind power forecasting, and offered the potential for cost-recovery of integration charges on a case-by-case basis if other prerequisites were met. FERC has also held technical conferences to explore how to encourage flexibility in generation and to explore the potential need for capacity markets. Both issues are regarded as critical to address, as discussed in an IEA Wind Task 25 paper [157].

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77. See *http://www.nerc.com/comm/PC/Pages/Integration-of-Variable-Generation-Task-Force-(IVGTF)-2013.aspx* for more information.

78. Reliability standards are posted on NERC's web site at *http://www.nerc.com/pa/Stand/Pages/default.aspx*

IEEE

The Power and Energy Society of the Institute of Electrical and Electronics Engineers—now known simply as IEEE—has sponsored several wind power "super sessions" at its annual General Meetings. On alternating years, the November/December issue of *Power and Energy Magazine* is devoted to wind integration issues, with the 2013 magazine the fifth such issue. The Wind Power Coordinating Committee of the IEEE Power and Energy Society was chartered in 2005 and later expanded to include solar power. Expanded interest in wind integration is evidenced by the large and increasing number of wind-related research papers in journal publications. In addition, the *Journal of Sustainable Energy* was launched in 2010 and is devoted to wind power and other renewable technologies. There has been a significant increase in journal articles related to wind integration in the years leading up to 2013.

2.7.6 Conclusions

The electric power network operates reliably with high wind contributions (10% and higher), with minimal impacts on network operating costs. Many sites with the nation's best wind energy resources have minimal or no access to electrical transmission facilities. System operators are implementing methods to accommodate increased penetration of wind power. The experiences of grid operators that already have large amounts of wind power can benefit operators in areas where wind will expand over the coming decades. Some key lessons learned from experience with wind that confirms the results of integration studies are:

- Sub-hourly dispatch and interchange make it easier and less expensive to integrate high penetrations of wind power.
- Market designs have continued to evolve. Wind power is now part of the energy market and the security-constrained economic dispatch.
- Additional market features—such as look-ahead dispatch or other means to incentivize flexibility—are being implemented or investigated.
- Operational coordination between balancing areas—especially small ones—can facilitate wind integration substantially, and the 15-minute scheduling promulgated by FERC Order 764 is helping achieve this.
- When incorporated into operational practice, more accurate wind power forecasts can help cost-effectively integrate wind power.
- Advanced wind turbine controls can provide reactive power support, synthetic inertia, governor response, and regulation, further augmenting power system flexibility and reducing the cost of using large amounts of wind generation.
- More operational flexibility is needed at high wind power penetrations. In some cases, this flexibility may already exist and can simply be deployed if sufficient incentives are in place—or this flexibility can be provided by the wind power plants themselves. In other cases, additional flexibility may be needed.
- Transmission upgrades or expansion may be needed to increase system flexibility or to access the best wind resources.
- In addition to physical flexibility, institutional and market characteristics might inhibit access to flexibility.

Section 4.5 of the *Wind Vision* roadmap discusses several actions related to wind integration and required to achieve the *Wind Vision Study Scenario* deployment levels, including:

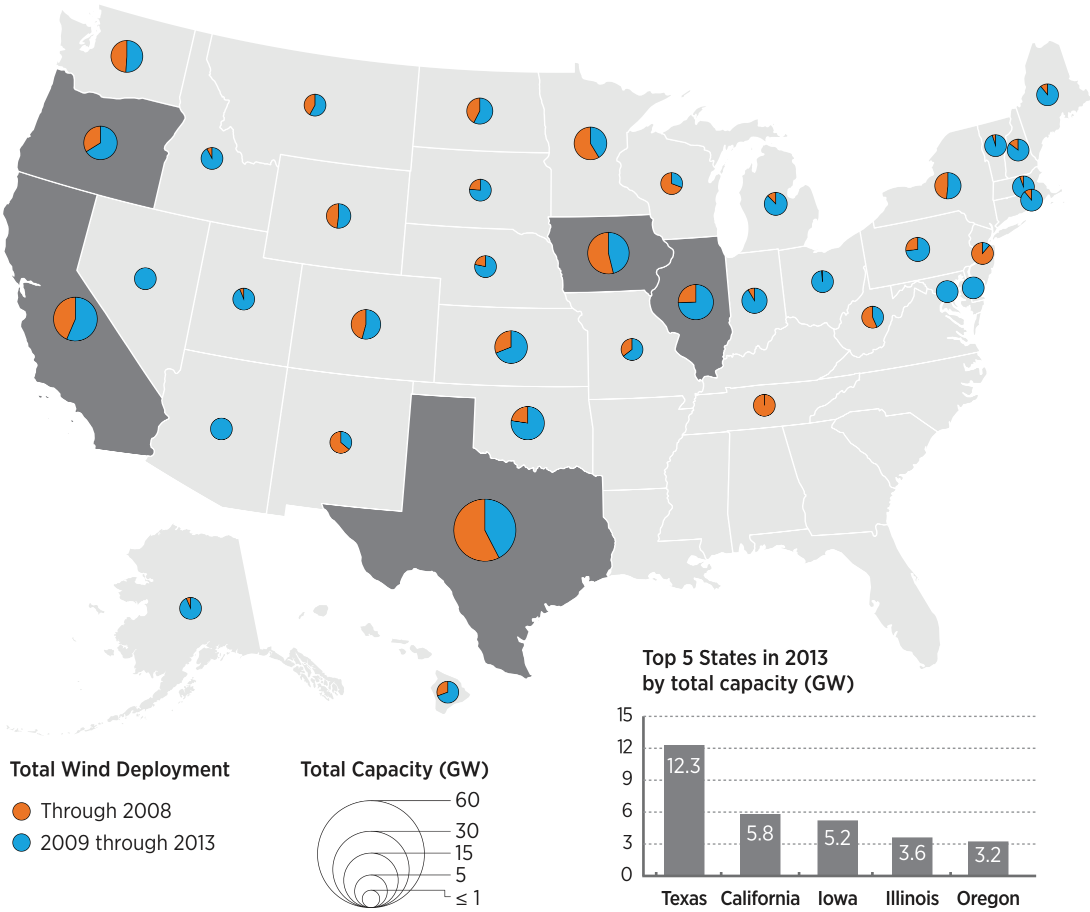
- Collaborating with the electric power sector to encourage sufficient transmission and provide for economically efficient operation of the bulk power system over broad geographic and electrical regions;
- Collaborating with the electric power sector to promote increased flexibility from all resources;
- Collaborating with the electric power sector to encourage operating practices and market structures that increase cost-effectiveness of power system operation with high levels of wind power;
- Optimizing wind power plant equipment and control strategies to facilitate integration;
- Developing optimized offshore wind grid architecture and integration strategies; and
- Improving distributed wind grid integration and increasing utility confidence in distributed wind systems.

2.8 Wind Siting, Permitting, and Deployment

Throughout the history of commercial wind power development, much has been learned about the impacts of wind turbines on their surroundings. Methods to address these impacts have been developed through investment in studies to understand impact risks. This research has led to improved siting practices and evaluation of avoidance and minimization measures, coupled with mitigation strategies. The wind power industry has implemented such strategies and continues to address siting and environmental issues.

Siting impacts have been evaluated and are manageable when project development is done responsibly.

Experience and research have shown that impacts of wind development on wildlife, public health, and local communities can largely be managed with avoidance, minimization, and mitigation strategies, as well as through communication.[79] These strategies include evolutions in siting practices, technology



Note: Distributed wind projects with less than 1 MW have been installed in all 50 states.

Source: National Renewable Energy Laboratory

Figure 2-43. Utility-scale wind deployment through 2013

79. The USFWS *Land-based Wind Energy Guidelines* [163] define mitigation, specific to the wind energy guidelines as “Avoiding or minimizing significant adverse impacts, and when appropriate, compensating for unavoidable significant adverse impacts.” This is a broad definition which may cause confusion to readers without explicit understanding of impact assessment. Within the *Wind Vision,* additional terms such as ‘impact avoidance’ and ‘minimization’ are used to provide additional clarity. These are encompassed within the USFWS definition.

development, permitting processes, and operational procedures. With wind turbines over 1 MW in size deployed in many states by the end of 2013 (Figure 2-43), environmental and competing use concerns are increasingly important.[80]

This section provides detail on existing and continued efforts to address these concerns. Section 2.8.1 discusses public acceptance and environmental concerns associated with wind power including siting and permitting considerations, and public perception and community impact. Section 2.8.2 discusses the varied and complex regulatory environment affecting wind power.

2.8.1 Public Acceptance and Environmental Concerns

Wind generation capacity increased fivefold between 2008 and 2013. Although wind plant development has been concentrated in California, the Midwest, and Texas, wind turbines are operating in every region of the United States.[81] Wind turbines are being installed more widely and, in many cases, in closer proximity to people and communities. Advances in wind turbine technology are also facilitating expanded development interest in locations not considered previously, opening up the whole nation to potential wind development.

A March 2013 Gallup poll found that more than 71% of Americans think the United States should place more emphasis on wind power development. This percentage is slightly lower than related results for solar power, but above all other forms of domestic energy production. Favorable opinions of wind power were equal to or just below solar in all regions except for the South, in which residents slightly favor more emphasis on natural gas development [158]. More directed polling, especially when combined with informing survey recipients about the benefits and impacts of different energy options, typically results in high selections of wind [90]. Such polling does have regional variation, and results change when the questions focus on local development. Research specifically examining offshore wind development shows similar trends [159, 160, 161, 162].

The widespread use of distributed wind is significant and represents the leading edge of the interface between humans and wind power. Some states in the Southeast do not have large wind plants, but they all have some type of distributed wind system. The wide geographic spread of these distributed wind systems creates familiarity with wind turbines, reducing uncertainty and public concerns and paving the way for development of larger wind plants [164].

Local development helps support the view of wind as a viable technology that brings economic benefits, but it can also be a flashpoint for opposition. Focus groups conducted in New England and other areas show people's views of wind are dependent upon their local surroundings and communities [165]. Studies demonstrate that when wind project development includes active community engagement, public reactions are more favorable [165, 166].

Rapid increases in wind development have been accompanied by the formation of anti-wind organizations. These typically small and vocal organizations address local concerns regarding wind development, and express a desire to provide an alternative viewpoint. Open debate can eventually lead to stronger community buy-in as concerns are addressed. The challenge, however, is ensuring that information from both sides is fact-based, accurate, scientifically defensible, and accessible. A failure to reach these standards can cause delays or failures in wind permitting and development processes, and even ordinances and legislation that affect wind development based on poor understanding of potential impact.

Environmental Impacts of Wind Deployment

As with any form of energy generation, wind power development and operation can have impacts to the natural surroundings. Environmental impacts most commonly associated with wind development and operations are addressed in the following section.

The wind industry has invested significant resources to investigate and predict impacts to wildlife and to avoid, minimize, or compensate for these predicted impacts as appropriate. As is true of all energy sources, electricity from wind power does have impacts to wildlife. Specific wildlife concerns for wind are collision mortality of birds and bats (direct

80. Although not reflected in the figure, smaller distributed wind systems have been installed in every state.

81. As reflected in Figure 2-41, the Southeast does not have wind turbines greater than 1 MW as of 2013. The region does, however, have smaller distributed wind installations in operation as of 2013.

impacts to individuals) and indirect effects associated with habitat fragmentation and displacement of sensitive wildlife species [167]. Some examples of initiatives that have improved understanding of impacts of wind power on wildlife and provided measures to reduce those impacts include:

- U.S. Fish and Wildlife Service (USFWS) Wind Turbine Guidelines Federal Advisory Committee. Formed by the USFWS, this committee facilitated agreement among the industry, USFWS, state wildlife officials, conservation organizations, science advisors, and tribes on recommendations for dealing with wind power. This consensus served as the basis for the USFWS *Land-based Wind Energy Guidelines* [163], the most extensive set of wildlife-related guidelines developed for an energy industry as of 2013.
- In 2003, the wind industry partnered with federal agencies and the largest bat conservation organizations to found the *Bats and Wind Energy Cooperative*. In 2008, the wind industry helped found the *American Wind Wildlife Institute (AWWI)*, a partnership between wind power companies and the nation's largest science-based conservation and environmental groups. AWWI invests in applied scientific research to reduce uncertainty and develop minimization and mitigation strategies.
- The *National Wind Coordinating Collaborative* Wildlife Workgroup, facilitated by AWWI, is a joint effort of the wind industry, federal conservation agencies, other industry representatives, state officials, and conservation groups that conducts outreach on wind wildlife science and conservation.

Despite these efforts, uncertainty remains regarding the impacts of wind power development on wildlife. One challenge still to be addressed is the relationship between pre-construction activity and post-construction impacts, particularly with respect to bird and bat collisions [168]. Solutions to address this challenge are in development.[82] Regardless, the process of siting wind power plants has evolved significantly since the early days of the industry, when little was known about the interactions between wildlife and turbines. Further progress can be made with increased information sharing and peer-reviewed, applied studies that reduce uncertainty and establish solutions to minimize and mitigate risk and impacts to wildlife.

Impacts on Avian Species

While collisions with wind turbines are associated with bird mortality, mortality rates for birds at land-based wind plants average between three and five birds per MW per year, and no plant has reported an average greater than 14 birds per MW per year [169, 168, 170, 171]. Songbirds account for approximately 60 percent of all bird collision mortality [168], but current mortality levels constitute a very small percentage, typically <0.02%, of the total populations of those species [172, 173, 169, 174]. The more recent studies by Erickson et al. 2014 [169] and Loss et al. 2013 [171] support the conclusion that bird mortality is lower than earlier reported estimates. Overall, bird collision mortalities are low relative to other human-related bird mortalities (Table 2-8).

Table 2-8. Estimated Annual Bird Mortality Rates from Collisions with Engineered Structures

Structure	Average Mortality Rates (million birds/year)
Wind turbines	0.2[a]
Communications and other towers	6.8[b]
Power lines	130[c]
Buildings	300–1,000[d]

a. Source: Loss [171]
b. Source: Longcore [175]
c. Source: Erickson [169]
d. Source: Loss [171]

Eagles

Eagle mortality rates at some wind power plants have been higher than anticipated, particularly at older plants such as the Altamont Wind Resource Area in California, and this creates the impression that large numbers of eagles are at risk at all wind power plants. Early wind development in areas like Altamont experienced high eagle mortality.[83] As wind power has matured, however, the wind industry and regulatory agencies have been working to reduce impacts by

82. See AWWI's Information Center at *www.awwi.org*.

83. More information about avian mortality at early wind plants can be found in the proceedings of National Avian-Wind Power Planning Meeting held in July of 1994 to discuss this important topic. A link to the proceedings can be found at *http://qa.gpp.reisys.com/proceedings-national-avian-wind-power-planning-meeting-lakewood-colorado-july-20-21-1994*. A second meeting was held in September of 1995 to discuss research topics to address mortality issues, the proceedings for this meeting can be found at *https://nationalwind.org/research/meetings/*

modifying siting and operations procedures. Changes in wind turbine technology such as the use of taller tubular towers and slower rotor turbines have also reduced raptor impacts in locations such as Altamont [172]. This change is documented by the reduced numbers of raptor fatalities resulting from repowering at Altamont [170]. While eagles do occasionally collide with wind turbine blades, data indicate this is actually a rare event. As of 2014, however, there were no systematic, unbiased estimates of the relative frequency and magnitude of the various sources of eagle mortality, including wind power development. This gap can make it hard to predict the relative impact from expanded wind development.

That said, Pagel et al. (2013) [176] report 79 golden eagle fatalities and six bald eagle fatalities at wind power plants other than Altamont since 1997. This includes one bald eagle fatality at a single storm-damaged turbine on a wildlife refuge. Although Pagel et al. consider these numbers to be an underestimate, a survey of publicly available data on bald and golden eagle fatalities from anthropogenic causes (e.g., power lines, vehicles, lead, etc.) indicates that fatalities at wind plants are a small percentage of total annual mortality of both bald and golden eagles [177]. All impacts are assumed to be cumulative,[84] and expanded wind development could result in population concerns for certain regions where populations are already under stress. The eagle take[85] permit process, however, requires any losses of bald and golden eagles at wind farms to be offset by reducing mortality from other existing, unmitigated sources of eagle mortality. This stipulation ensures there is no-net-loss to eagle populations.

The USFWS enforces the Endangered Species Act (ESA), Migratory Bird Treaty Act (MBTA), and the Bald and Golden Eagle Protection Act (Eagle Act). In March 2012, USFWS issued a document outlining voluntary guidelines to help project developers avoid and minimize the impacts of land-based wind plants on migratory birds and other species of concern and their habitats [163]. Adherence to the Wind Energy Guidelines does not relieve any individual, company, or agency of its responsibility to comply with regulations such as permitting obligations pursuant to the ESA, Eagle Act, or MBTA, or obtaining a permit. The USFWS, however, will take adherence to the guidelines “into account when exercising [enforcement] discretion with respect to [a] potential referral” under the MBTA [163].

The Eagle Act provides a strict level of protection for both bald and golden eagle species, and, as mentioned previously, USFWS has instituted a “no net loss” policy for golden eagles. This policy requires developers to offset every golden eagle killed at a wind plant by reducing mortality from another source or by increasing eagle productivity. In April 2013, the USFWS released its “Eagle Conservation Plan Guidance Module 1 – Land-based Wind Energy Version 2” [178]. The guidance recommends conservation practices for siting, construction, and operations of wind power plants that can support developers to obtain eagle take permits in compliance with the Eagle Act. Permit regulations require wind plants to show that any take is unavoidable after adopting avoidance and minimization measures referred to as “advanced conservation practices.” Because of the absence of appropriate data, however, USFWS has yet to finalize any advanced conservation practices. There are also permit uncertainties with respect to risk assessment methodologies, assessment models, and the available compensatory options for an unavoidable take. While the current regulations were originally promulgated in 2009, only one permit has been issued to a wind power plant through 2014, reflecting this ambiguity.

Prairie Chicken and Sage Grouse

It has been hypothesized that an operating wind power plant and related habitat disturbance could displace certain avian species and cause potential population decline. As of 2013, data for this theory are inconclusive. Certain species of prairie grouse—in particular, greater sage grouse and both greater and lesser prairie chickens—are thought to avoid breeding sites in the proximity of tall structures, but few

84. Although the impact of a specific wind plant is expected to be low compared to other anthropogenic cause, in areas where eagles are already under stress the sum of all of these impacts, especially in the light of expanded wind deployment as depicted within this Vision scenarios, may be a reason of concern for populations in specific regions.

85. Under the Bald and Golden Eagle Protection Act, the term “take” includes, “pursue, shoot, shoot at, poison, wound, kill, capture, trap, collect, molest or disturb” (16 U.S.C. 668c; 50 CFR 22.3). “Disturb” means “to agitate or bother a bald or golden eagle to a degree that causes, or is likely to cause, based on the best scientific information available, 1) injury to an eagle; 2) a decrease in its productivity, by substantially interfering with normal breeding, feeding, or sheltering behavior; or 3) nest abandonment, by substantially interfering with normal breeding, feeding, or sheltering behavior.”

published studies have tested this hypothesis with specific regard to wind power plants [173, 179]. Other studies [180, 181] have questioned whether the impacts are from the tall structures themselves, versus other factors like road noise. Recent research specific to greater prairie chickens indicates the species is not strongly affected by wind power development. Several published studies focusing on central Kansas show a slight reduction of breeding areas near turbine development, but no negative effect on nest site selection and—in some cases—increased female survival rates [182, 183].

Many prairie chicken and grouse grassland habitat areas across the Midwest and West have been identified as potentially ideal for development of wind power and other energy plants. Stakeholder groups generally agree that there is a need to better understand the potential and actual impacts of development of wind power plants on prairie chickens and sage grouse in order to identify possible mitigation approaches. Several groups—including the National Wind Coordinating Collaborative, AWWI, and the Bureau of Land Management (BLM)—are funding research to more fully understand the potential impact wind development has on the populations of these species [184]. Land use and conservation planning efforts undertaken by the BLM and state wildlife agencies, may restrict or eliminate the potential for wind energy development in the historic range of these species in order to reduce the likelihood for ESA designation. The benefit, however, is that these efforts also may provide clarity on wind development opportunities over the long-term.

Whooping Crane

Recognizing that some of the best wind resources in the country overlap with the migration corridor of the Whooping Crane, a group of 15 developers worked in collaboration with the USFWS and state agencies to develop a multi-species regional programmatic Habitat Conservation Plan (HCP).[86] This HCP covers wind power development activities for an area extending 1,500 miles north/south—from the Texas coast to the Canadian border—and 200 miles wide This HCP is anticipated to provide legal certainty for wind developers, while including essential planning and conservation measures.

Impacts on Bat Species

Bat mortality associated with wind plants can be higher than bird mortality and shows greater variation both within and among regions. Two wind plants in the eastern United States have reported averages of up to 30 bat fatalities per MW per year, but other plants in the East have reported one to two bats per MW per year [185]. Migratory tree bats constitute the majority of bat fatalities accounted for at wind plants. A lack of knowledge about population size for these species and about the impact of non-wind-related issues—such as white nose syndrome, habitat loss, conventional energy development impacts, and other anthropogenic impacts—have raised concerns that tree bats may be unable to sustain current mortality rates [186]. Without this baseline information, however, there is no way for the scientific community to come to a conclusion either way. Research is identifying discernible patterns in bat mortality at wind power plants, including a correlation between fatalities and migratory and mating behaviors.[87] In 2011, the USFWS released "Indiana Bat Section 7 and Section 10 Guidance for Wind Energy Projects" [187] to help USFWS biologists assess the impacts of wind power plants on the endangered Indiana bat. These guidelines are considered an interim step needed until there is a more complete understanding of Indiana bat-wind plant interactions [178]. The number of bat species being considered for ESA listing by the USFWS is increasing as of 2013, due largely to White-nose syndrome as well as anthropogenic causes. Listing of these species will result in federal oversight of wind-wildlife issues on private lands and could complicate the permitting and deployment process for new wind systems, as well as potentially impact operations in the existing fleet.

Recognizing the need to address conservation concerns regarding bat impacts, the wind industry is engaged with USFWS, state wildlife agencies, and other stakeholders to develop a multi-species, multi-state regional HCP to cover activities related to wind energy development and operations throughout the eight-state Midwest region. As of 2014, the wind industry and scientific and conservation communities were testing promising methods that have reduced

86. HCPs under Section 10(a)(1)(B) of the ESA provide for partnerships with non-federal parties to conserve the ecosystems upon which listed species depend, ultimately contributing to their recovery. HCPs are required as part of an application for an incidental take permit and describe the anticipated effects of the proposed taking; how those impacts will be minimized, or mitigated; and how the HCP is to be funded.

87. *www.fort.usgs.gov/BatsWindmills/*

bat mortality by more than 50% in field testing at several sites [185]. Continued investigation and data collection will support enhanced understanding that can help wind developers avoid and minimize bat mortality.

Impacts on Other Species

Impacts of wind development to wildlife species other than bats and birds are not well understood [167]. As discussed later in this section, studies indicate that direct loss of habitat from turbine pads, access roads, and transmission is a small percentage of the total wind plant area. Other potential impacts from land-based wind including indirect effects such as displacement or demographic decline owing to disturbance or the fragmentation of suitable habitat need to be determined and verified by additional research. Although doing so is outside the focus of the *Wind Vision*, the potential impacts of wind development should be evaluated within a construct that considers the potential environmental impacts of other energy development.

Impacts of Offshore Wind Development

Wildlife concerns associated with offshore wind include effects on migratory birds, marine mammals, essential fish habitat, and protected and threatened species such as sea turtles. Benthic communities, such as warm and cold water corals that have endangered or threatened status would also need to be considered. Bird strikes are likely to be a key offshore wind regulatory issue in the United States, but experience from Europe indicates that migratory bird collisions may occur at a lower rate for offshore than for land-based wind [188]. According to published literature, most seabirds and waterfowl tend to fly below the rotor swept area, while nocturnally migrating land and shorebirds usually fly above the rotor swept area [189]. Additional concerns include offshore wind plants displacing waterfowl from foraging habitat or acting as barriers along migratory pathways. Initial offshore surveys along the East Coast indicate avian activity is more prevalent closer to shore and lower beyond 10 miles from shore [190]. Given the current lack of existing general data, BOEM provides guidance for avian surveys required for the project review approval process.[88]

Sufficient—though limited—data suggest that bats migrate offshore and use islands, ships, and other offshore structures as opportunistic or deliberate stopover sites. Bats may also forage offshore during migration, perhaps to avoid competition or to exploit certain food sources [191]. The potential impact of offshore wind development on bat species of interest is, however, unknown, and more directed research is needed.

The construction and operation of offshore wind plants also pose the risk of harassment or injury under the Marine Mammal Protection Act and the ESA, particularly during construction and maintenance. Developers of offshore wind will likely be required to apply for "take" permits under the ESA and/or incidental harassment authorization for harming marine mammals under the Marine Mammal Protection Act (NOAA Fisheries). At a minimum, developers will be responsible for consulting with appropriate parties under Section 7 of the ESA.[89]

The ESA offers a broad definition of "take," including sound-related harassment. As such, offshore wind developers face particular concern for the North Atlantic right whale. With a total population of about 450, the right whale is listed as endangered under the ESA and as a depleted species under the Marine Mammal Protection Act.[90] As of 2014, there are few definitive studies correlating the level of sound from operation of wind turbines with behavioral changes in marine mammals. Certain geophysical surveys and pile driving during construction of offshore wind plants pose the risk of auditory harassment or injury—as defined by the Marine Mammal Protection Act and the ESA [192]—to marine mammals, sea turtles, and some fish. Survey and construction vessels also pose collision risks for whales, other marine mammals, and sea turtles [192]. To help address various concerns about marine mammals, BOEM provides guidance for pre-construction surveys to establish a baseline for the presence and activity of marine mammal species.[91]

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88. BOEM's constructions and operations guidance is available at: *http://www.boem.gov/National-and-Regional-Guidelines-for-Renewable-Energy-Activities/*

89. Section 7 of the ESA provides guidance for interagency cooperation on issues related to the ESA. A summary of Section 7 is available at *http://www.fws.gov/endangered/laws-policies/section-7.html*.

90. NOAA Fisheries, *www.nmfs.noaa.gov/pr/species/mammals/cetaceans/rightwhale_northatlantic.htm*. Accessed June 4, 2014.

91. *http://www.boem.gov/National-and-Regional-Guidelines-for-Renewable-Energy-Activities/*

Pre-construction baseline wildlife surveys and ongoing monitoring and mitigation, including curtailing construction activities upon the approach of marine mammals, can help reduce the risk of offshore wind development to such species. BOEM requires measures to protect Northern Atlantic right whales from collisions and from survey and construction noise as Standard Operating Conditions of each new offshore wind lease [193]. [92,93]

Siting and Permitting Mixed Use Considerations

Beyond the local environmental impacts of wind deployment, there are additional considerations that need to be addressed as part of state or local permitting requirements. The following highlights the most important of these permitting questions.

Sound

Turbine sound is typically one of the greatest nuisance impacts associated with wind power [166]. As of 2013, however, global peer-reviewed scientific data and independent studies consistently concluded that sound from wind plants has no direct impact on physical human health [194, 195, 196, 197, 198].

For example, the Australian National Health and Medical Research Council issued in 2010 a draft report on the results of an independent review of available scientific literature examining the relationship between wind power and health. The Council found "no consistent direct evidence that exposure to wind plants was associated with any health outcome" and noted that the "few associations reported by individual studies could have been due to chance" [197].

In 2012, the Massachusetts Department of Environmental Protection and Department of Public Health commissioned a panel of experts in public health, epidemiology, toxicology, neurology and sleep medicine, neuroscience, and mechanical engineering to analyze health effects of turbines, including those resulting from noise. The panel reviewed existing studies, including both peer-reviewed and non-peer-reviewed literature. The panel found that the strongest epidemiological study suggests there is no association between noise from wind turbines and measures of psychological distress or mental health, and that none of the limited epidemiological evidence reviewed suggests an association between noise from wind turbines and pain or stiffness, diabetes, high blood pressure, tinnitus, hearing impairment, cardiovascular disease, and headaches or migraines [199].

Additional studies, including one by a scientific panel convened by AWEA and the Canadian Wind Energy Association, have also concluded that sound from wind turbines does not cause negative health impacts [200].

While scientific evidence does not demonstrate any health risks, some residents living close to wind turbines have expressed annoyance attributed to turbine sound [201]. Some studies have documented annoyance and confirmed its correlation with turbine sounds, but have also found correlations with attitudes towards and visibility of specific wind plants [202, 203, 204]. Two studies [205, 206] have documented that complaints associated with wind turbine noise can be impacted by the availability of information—accurate or inaccurate—about the potential impacts of wind noise. This study included the finding of physical symptoms in control groups not subjected to such noise. Even with this research, however, turbine manufacturers are working to reduce mechanical noise (e.g., from generators and gearboxes) as well as aerodynamic noise to help preempt concerns.

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92. The Conservation Law Foundation, Natural Resources Defense Council, National Wildlife Federation and Deepwater Wind, LLC, reached an agreement in May 2014 to implement additional protections for endangered North Atlantic right whales during pre-construction activities for the 500-MW Deepwater ONE offshore wind plant, which will be developed off the Rhode Island and Massachusetts coasts (*http://www.clf.org/right-whales-offshore-wind*). The agreement reduces the threat to right whales by restricting meteorological tower construction and other site activities during the peak foraging season, when whales venture to southern New England waters to feed. During other times of the year, when the whales frequent the area less, the activities may proceed under additional protective measures. These measures include enhanced real-time human monitoring for whale activity in the site area; restriction of pile driving activities to daylight hours when whales can be spotted; use of noise-reducing tools and technologies; and a lower speed limit for vessels during periods in the spring when North Atlantic right whales have been known to frequent Rhode Island Sound. A separate October 2013 agreement between Deepwater Wind and the Conservation Law Foundation restricts all construction activities for the 30-MW Block Island Wind plant foundation during the month of April.

    In 2012, a coalition led by the Conservation Law Foundation, the Natural Resources Defense Council and the National Wildlife Federation, working with Deepwater Wind, Energy Management, Inc. (owner of Cape Wind in Massachusetts), and NRG Bluewater Wind, drafted a similar set of protective measures that developers agreed to implement in the Mid-Atlantic Wind Energy Areas, which stretch from New Jersey to Virginia.

93. *http://www.boem.gov/Commercial-Wind-Leasing-Offshore-Massachusetts/*

Shadow Flicker

Shadow flicker results when the rotating blades of wind turbines cast moving shadows on the ground or on structures [207]. The phenomenon exists for some daily period of time at all wind sites if there is enough sunlight and the blades are rotating, but is more acute at high latitudes. In high latitude locations, the sun is in a low position on the horizon for a greater amount of time, resulting in a longer potential wind blade shadow. Shadow flicker is also more common in early morning and evenings, and can vary relative to surrounding structures and vegetation.

Nuisance complaints of flicker include anecdotal reports of nausea and vertigo, and the IEA [166] identifies shadow flicker as a nuisance. A study completed for the U.K. Department of Energy and Climate Change, however, concluded that, "...the frequency of the flickering caused by the wind turbine rotation is such that it should not cause a significant risk to health" [208]. Though the relationship between flicker and epileptic seizures has been questioned, there is no scientific evidence to support these claims. The strobe rates generally necessary to cause seizures in people with photosensitive epilepsy are 5-30 flashes per second [209], and utility-scale wind turbine blades cannot rotate this quickly.

The potential impact of shadow flicker is dependent on micro-siting. Wind plant designers often model where shadows might fall throughout the year in order to minimize potential impact on homes or structures. In many cases, setback distances in community ordinances and safety and sound setbacks for utility-scale wind projects usually place turbines far enough from structures to avoid flicker impacts. Although some controlled level of flicker is generally accepted in planning documents [207], mitigation measures can also be taken to reduce potential impacts. These measures may include flicker-specific setbacks, vegetative buffers, or the curtailment of the turbine during times of highest impact.

Land Use

There are several ways to consider the amount of land actually required to implement a wind plant. This requirement is project- and location-specific, but land use of wind plants can generally be broken into the following impact zones:

- **Leased Land:** This designation applies to all land that may be owned or leased for a proposed or operating wind plant. This is typically the largest potential area and may include land that is optioned by the developer but will not be developed as part of the wind plant. In almost all cases, this land will have multiple uses and only the wind development rights will be subject to the lease.
- **Plant or Facility Boundary:** This accounts for the legal boundary of the wind plant and may represent landowners who are being compensated for use of land related to a wind project. Because of the spacing of wind turbines, most of this area is not directly impacted by the plant and may have other economic uses, such as farming or ranching. Wind plants are not typically fenced because of their size, but restricted access gates or other access limitations are often used. Research indicates that the average plant boundary for a land-based wind plant[94] is 0.34 km^2/MW (85.24 acres/MW) [210]. For offshore wind plants, a range of values between 0.20 and 0.60 km^2/MW (49.4 to 148.2 acres/MW) have been proposed for projects along the Eastern seaboard [70, 71, 72, 73].
- **Land Transformation Areas:** This is the area of land that is considered disturbed from an environmental perspective. This area of disturbance will vary widely, depending on local ground cover near a wind plant. For example, in forests, more clearing may be required for roads, transmission upgrades, and safety setbacks, causing a greater impact then the same plant installed at a non-forested site. An analysis, using satellite images of land-based wind plants, completed by the U.S. Geological Service indicates that land transformation varies between 0.0011 and 0.043 km^2/MW (0.27–10.63 acres/MW), depending on considerations such as land cover (forest or farmland) and topography (Mesa or flat) [211].
- **Wildlife Disturbance Areas:** This represents the area within which wildlife may be disturbed. The wildlife disturbance area depends on habitat type and needs of the species within a project location, as well as sensitivity to human activity. In locations with wide-ranging species, such as eagles, the potential disturbance area can be quite large as compared to a site with narrow-ranging species,

94. The average value provided by Denholm is based on the project defined facility boundary for 161 specific projects totaling 15,871 turbines and 25,438 MW of installed capacity. The specific facility boundary for a specific project however can vary greatly from this value as is described in the full report.

such as turtles or salamanders, or those that are not susceptible to human disturbance.

- **Temporarily Disturbed Land:** The "temporarily disturbed" designation applies to the land area that will be used during construction of a wind plant but then returned to its original or an improved condition. This would include laydown yards for receiving the wind turbines and towers, crane pads, and electrical cable trenching. The expected temporary construction impact of a wind plant is about 0.007 km^2/MW (1.73 acres/MW), larger than the operational impact [210].
- **Operational Impacted Land:** This is the amount of land used for permanent structures such as access roads, tower foundation pads, and transformer pads. Operationally impacted land cannot be used for other purposes during the life of the wind plant. The expected operational impact of a wind plant is about 0.003 km^2/MW (0.74 acres/MW) [210]. The disposition of the wind plant after its operational life is determined by the contractual arrangements for decommissioning, but could include the removal of all surface features of the turbine foundation, roads, and other facilities. Complete removal may not be required if the land could be used to develop new wind assets through repowering [29]. The operational boundaries for offshore wind projects and how these boundaries will impact other uses have not been fully resolved and may vary based on plant location and jurisdiction.

With the exception of the range designated for the *Plant or Facility Boundary*, there are no specific numbers available for the impact zones created by offshore wind. The primary reason is that no U.S.-based offshore wind plants have been implemented, and issues around access and alternative use are still largely undefined. Within the boundaries of offshore wind plants, some restrictions are likely—such as changes to certain fishing practices—though other activities will still be permitted. Unlike land-based wind development, which has largely been undertaken on private land, offshore wind development will take place in public waters. This will require a formalized process to determine what additional water area uses will be acceptable.

The idea that wind power consumes large tracts of land results from a misconception that the entire land area "encumbered" by a wind lease is isolated from other uses, which is not the case. Although there are different ways to define the footprint of a wind plant, about 99% of land around a wind plant can be used for other activities, such as farming, ranching, and recreational activities [210]. Additional siting considerations—such as access road layout, land use during installation, potential long-term farming improvements, and current irrigation systems—need to be incorporated into all land lease contracts but are typically designed to mitigate the long-term impact to other land uses.

Radar and Aviation

For nearly a decade, government agencies have sought to balance the nation's need for new energy resources and the demands of critical air surveillance missions. Issues considered include flight safety, aerial monitoring of severe weather conditions, commerce, and control of U.S. borders and skies. While the federal government has worked to develop policy that ensures wind turbines and radars can co-exist, air surveillance and weather radars are impacted by wind power plants [212]. Some interference effects of wind turbines on radar systems include the inhibition of target detection, the generation of false targets, interference with target tracking, and hindrance of critical weather forecasts. In extreme cases, turbines have also caused significant electromagnetic issues. Interactions between wind turbines and aviation can impact government missions such as homeland security and defense (including training facilities and test ranges), air traffic control, flight safety operations, weather forecasting, maritime patrol, law enforcement, communications, and infrastructure protection. Potential issues have been addressed though siting requirements implemented by several federal agencies.

In 2008, the only widely used mitigation strategy was to ensure that wind turbines were located out of the line of sight of any radar. As a means to develop alternative mitigation strategies, the Interagency Field Test and Evaluation (IFT&E) program was implemented by the DOE, U.S. Department of Defense (DoD), U.S. Department of Homeland Security, and the Federal Aviation Administration's (FAA) with collaboration and assistance from NOAA with the goals to characterize the impacts of wind on air surveillance radars, assess near term mitigation strategies and increase technical understanding to advance development of long term mitigation strategies [212]. Through the implementation of a series of flight based field tests, several potential mitigation strategies were considered and show to improve, but not eliminate the impacts of wind turbine operation in proximity to wind farms. Infill radars to restore a loss in radar coverage in the vicinity of a wind plant and replacement radars, upgrading the identified radar technology, were both shown to improve detection performance. Other approaches including wind turbine-specific technologies such as radar-absorbing materials or coatings, structure shaping, wind plant layout design, and wind turbine-to-radar data-control schemes have also been considered but were not included in field based assessments completed to date. Several radar and software upgrades were evaluated with little documented impact, although alternative upgrade approaches may be more successful [212].

Federal agencies have instituted programs to identify new capabilities and help address radar issues related to wind turbines. These include the North American Air Domain Awareness Surveillance Analysis of Alternatives, the NOAA Multi-Function Phased Array Radar initiative, and the FAA's NextGen Surveillance and Weather Radar Capability program. Other ongoing government radar stakeholder activities include initiatives that leverage the success of the U.S. Interagency Field Test and Evaluation program through the development of a national Wind-Radar Interference Strategic Planning framework (to track mitigation capability research, development, and strategies), as well as implementation of the interagency agreement to execute a Pilot Mitigation Project Initiative (minimizing industry and government risk in accepting industry funded mitigation solutions).

Improvements in the two primary review processes, the NOAA WSR-88D NexRad review process and the DoD's role in the FAA Obstruction Evaluation/Airport Airspace Analysis review process, have led to enhanced wind permitting procedures. NOAA developed an improved build zone database accessed through the DoD Preliminary Screening Tool on the FAA Obstruction Evaluation/Airport Airspace Analysis website. The FAA website also includes a capability to engage NOAA representatives in an early notification process via links to the National Telecommunications and Information Administration, NOAA's review process clearinghouse for wind-radar evaluations.

The DoD has revised its review process significantly by establishing the DoD Siting Clearinghouse, which provides a "one-stop-shop" for comprehensive, expedited evaluation of energy plants and their potential effect on DoD operations. The Clearinghouse's formal review process applies to projects filed with the Secretary of Transportation, under Section 44718 of title 49, U.S. Code (FAA obstruction evaluation process). It also applies to other projects proposed for construction within military training routes or special use airspace, whether on private, state, or federal property such as that managed by BLM. Operational impacts of wind turbines on DoD missions are determined by several DoD organizations in parallel. The DoD Siting Clearinghouse acts as the conduit between the FAA's Obstruction Evaluation Review Process and the wind developer. DoD uses two types of reviews, a formal review and an informal review.[95]

All land-based construction more than 200 feet tall, including wind turbines, needs to be assessed under the FAA's Obstruction Evaluation. FAA-approved lighting is also mandatory for structures over 200 feet, and updated lighting regulations are being considered for structures taller than 500 feet. Specific FAA regulations place additional requirements to site turbines in close proximity to airports. These regulations are complex and have many dependent requirements—such as the type of airport (commercial, military, or private), local terrain variations, and type of approach (precision instrument)—but they generally limit structure height in proximity to airports and/or controlled airspace. Several mitigation options have been proposed to reduce possible effects of nighttime lighting. These include directional shielding, permission to light only some towers versus all, and the use of airplane detection technology that turns on lights only when aircraft are in the area.

Communications Systems

There are two categories of communications that need to be evaluated during design and permitting for wind plants: television and radio reception for neighboring residents, and local microwave tower interference. Transmission from radio or TV broadcast frequencies can be influenced by obstacles between the transmitter and the receiver. Modern wind turbines blades are made primarily of composite materials so there is usually minimal impact on the transmission of electromagnetic radiation, e.g.,

95. Details on each review can be found at *www.acq.osd.mil/dodsc/contact/dod-review-process.html*.

radio or TV signals. Revolving turbine blades sited directly between transmission sources and receptors, however, can interfere with TV reception. This can be rectified by replacing the existing antenna with a larger, more powerful one; adding a reception booster to the antenna; or switching to cable or a satellite service. These solutions are typically required to be procured by the wind plant owner and are usually a condition to local or state permits.

Interference with microwave-based line-of-sight communications is also a potential concern. Wind plant developers are required by state and local permitting agencies, as well as many financing companies, to perform a communications impact analysis or equivalent to demonstrate that pathways between communicating towers are unobstructed prior to having wind project construction or operational permits approved. If a potential obstruction is identified, mitigation options can be applied either at the wind plant or with the microwave towers.

General Safety

As with any machinery, wind turbines can fail and result in safety issues. Although no industry wide, reference quality assessment of catastrophic wind turbine failures has been completed, they are considered rare events with fewer than 40 incidents identified in the modern turbine fleet of more than 40,000 turbines installed in the United States as of 2014. Modern wind turbines represent a significant investment, and high priority is placed on regular maintenance to reduce the chances of catastrophic failure. Turbines are equipped with sensors and data acquisition systems designed to turn the turbine off when any unusual operational condition occurs, typically before a catastrophic failure. In order to protect nearby structures and public safety, local municipalities, counties, and state regulators define safety setbacks to guard against impacts in the unlikely event of tower collapse, blade throw, and ice shedding. In areas where turbine or blade icing may occur, additional safety-related conditions may be requested or required [213].

Marine Safety

BOEM requires a detailed navigational risk assessment of each proposed wind project area to determine how current vessel traffic patterns and density may change as a result of the construction and operations of an offshore wind plant. Developers need to evaluate if the siting, construction, establishment, operations, maintenance, and/or decommissioning of wind power plants might cause or contribute to obstruction of or danger to navigation and/or affect the traditional use of a waterway. The U.S. Coast Guard is responsible for ensuring navigational safety for commercial and recreational vessels under the Ports and Waterways Safety Act, which extends 12 nautical miles from the U.S. coast. Buffers and navigational routing measures around offshore turbines minimize the risk of collision with turbines at sea and mitigate safety concerns associated with equipment failure. Automated Identification System transceivers may also be installed on wind turbines or buoys to mark a particular wind plant boundary feature, and restrictions on transit through wind plant areas may be imposed during periods of reduced visibility.

Public Perception and Community Impact

The final area of consideration is how the deployment of wind plants impacts public and community perception. Although some of these overlap conceptually with potential impacts identified in other sections, the areas of concern in this section are discussed primarily at the community level.

Visual Impacts

Surrounding property owners and the community often express concern about the visual impact of a wind plant. While most other potential impacts of wind development can be measured or at least discussed in quantitative terms, visual impacts are more qualitative and based on an individual's appreciation of and interaction with their surroundings. In addition to referencing research about the visual impacts of wind power such as those summarized in the 2011 International Panel on Climate Change special report on wind energy and climate change mitigation (e.g., Wiser 2011 [84]), project developers and communities commission visual impact assessments that provide a better understanding of what turbines may look like against different landscapes.

Without clear standards or guidance on how these visualizations are structured, it is difficult to assess potential impacts. To help address this, a set of common protocols for visual impact assessments were implemented by the Clean Energy States Alliance [214]. DOE supported the resulting guide issued by the Clean Energy States Alliance, "A Visual Impact Assessment Process for Wind Energy Projects." This document offers aesthetic impact assessment review methodology and guidance for developers, planners, and regulatory decision makers, and includes suggestions for establishing a clear and consistent visual impact review process. Additional stakeholder discussions have also provided useful information on ways to engage with communities about the visual impact of wind power development [165]. Tools have been developed to provide state-of-the-art visual impact assessments, including video representation.

Aviation avoidance lighting has also been highlighted as a visual annoyance for wind turbine installations. Mitigation options have been proposed to reduce the potential effects of nighttime lighting and several are under FAA review. These include some of the options discussed in the Radar and Aviation section, such as directional shielding, permission to light only some towers, and the use of airplane detection technology.

Other factors related to aesthetics and wind development include guidelines from State Historic Preservation Offices[96] and systems for evaluating projects proposed on public lands. Some states have separate jurisdictions to review and approve projects proposed for public lands.

Property Values

Given the long history of concern about the potential impacts of wind development on property value, the body of peer-reviewed literature investigating such impacts is increasing. The seminal work in this area, with the largest data set, was conducted by LBNL. This work found no statistical evidence of adverse property value effects resulting from views of and proximity to wind turbines after the turbines were constructed [215, 216, 217, 218]. Other peer-reviewed and academic studies also found no evidence of post-construction effects across a variety of techniques and residential transaction datasets [219, 220, 221, 222, 223, 224]. Courts in Canada (Kerry v. MPAC 2012) and Wisconsin (Realtors et al. v WI PSC 2014) made determinations that evidence of property value impacts was not sufficient to warrant overturning previous decisions. Three working papers in the European Union, however, do report impacts to home values in Germany [225], Denmark [226], and the United Kingdom [227]. These results imply that, in the United States and Canada, post-construction effects of wind turbines on the value of surrounding homes either do not exist, are too small for detection, or are sporadic (resulting in a small average percentage), while effects in some European countries are more pronounced. Analysis in the United States has, however, found some evidence of potential property value effects after a wind plant has been announced but prior to construction [222, 221, 218].

Local Economic Development

Data related to utility-scale wind development demonstrates numerous positive economic impacts [91, 228, 229]. The 2011 Slattery study [91] estimated economic impacts from 1.4 GW of wind power development in four rural counties in west Texas. The total economic activity to the local communities was estimated to be nearly $730 million over the assumed 20-year lifetime of the wind plants, or $0.52 million per MW of installed capacity.

Social and economic benefits from distributed and community wind plants typically remain in the local community. Distributed wind turbines normally rely on a local small business to install or develop the wind turbine system. In locations with high electric retail rates or the threat of electric rate increases, energy produced by an on-site distributed wind installation can offset electricity costs, lowering operating costs for the system owner (e.g., a local business). An NREL study found that community wind plants have increased local employment impacts during both the construction and operations periods compared to plants developed by parties from outside the local area. These employment related impacts range from 1.1 to 1.3 times higher for the construction phase and 1.1 to 2.8 times higher in the operations phase [229].

Competing Uses

As of 2013, most wind turbines are installed on land that was typically used for other purposes prior to the wind installation. Wind development on private lands results in compensation to the land owner for the potential loss of use of the land; private landowners receive an estimated $180 million annually in land lease payments from wind project developments [9]. Development on federal and state properties (both land and water) poses complications, since installation of the plant may impose restrictions or otherwise impact uses for the area, but affected parties do not have legal grounds to any direct compensation. For

96. One example is the New York State Historic Preservation Office guidelines for the assessment of historic and cultural resources associated with the development of wind plant projects in the state, available at *http://www.nysparks.com/shpo/environmental-review/*.

example, commercial and recreational fisheries are part of the culture and economy of coastal communities but receive no direct compensation from offshore development in federal waters because royalties are only paid to the appropriate state and federal government.[97] Such communities will want clear and accurate information about whether and how a proposed plant will affect the species of fish they target, how they fish, or where they have historically fished. Shipping lanes and navigation have also played a role in the development of current leasing zones for offshore wind, but rules have not been finalized to govern use of leasing areas for other activities. Another example of public sites in which proposed wind plants may cause conflicts are offshore and land-based DoD firing ranges, flight training, and exercise areas. To the extent possible, the impact of wind development on competing uses should be understood prior to project initiation, and developers should coordinate with the local community, land use and regulatory agencies, and other stakeholders during project conception, development, construction, and operation.

Summary

Competing use, public acceptance, and environmental concerns for wind plants can be addressed through careful and considered siting, which should include open collaboration with the community and its leaders. This will facilitate increased public involvement and understanding of best practices for wind installations. Additional activities that have proven effective in enhancing understanding of wind siting concerns include:

- Stakeholder engagement, including proactive development and dissemination of publicly accessible information about wind impacts and benefits through publications, electronic and social media, workshops, and outreach;
- National, state, and regional efforts to gather, analyze, and distribute information; and
- National and regional independent or consensus-based organization(s) that have helped improve the scientific research, facilitated discussions on wind-related impacts, and provided negotiated paths for implementation of locally appropriate best practices.

2.8.2 Regulatory Environment

The regulatory environment for wind project development is varied and complex, with an array of federal, state, and local rules that create uncertainties in development timelines and project development success. As with almost any development project, permitting is required. Since the United States uses a dispersed model of development approval that is regulated at the state or local level, permitting requirements vary based on project location and size. These variances, combined with differing levels of public involvement, can create a challenging regulatory environment. Section 5.5 of the *20% Wind Energy by 2030* report provided an overview of the siting and regulatory framework for wind power projects, highlighting related permitting processes and regulations.

The wind power community has addressed substantive siting and regulatory issues, but continued work is needed to reduce uncertainty and streamline siting and permitting.

While variance still prevails, local and state regulations are evolving as more wind opportunities are explored and deployed across the country. In January 2012, the National Association of Regulatory Utility Commissioners published a report summarizing land-based wind power siting and zoning practices in all 50 states and the District of Columbia [207]. The primary decision-making authority for land-based wind project permitting resides with local governments (known as Home Rule) in 26 states, and state governments (referred to as Dillon's Rule) in 22 states. Other states use shared local and state responsibility for permitting. The National Association of Regulatory Utility Commissioners report provides recommendations on siting and zoning best practices to help guide states in their processes. Other organizations have created similar guidance documents for wind power development, including The American Planning Association [230] and AWEA [231].

While several states have permitting processes for utility-scale land-based plants, few address distributed wind. Some states with distributed wind-focused grant programs have a defined permitting process for

97. Based on Code of Federal Regulations, Title 30, Chapter V, Subchapter B, Part 585, Subpart E, Section 585.540, wind projects between 3 nautical miles from the state boundary (typically between 3 nautical miles and 6 nautical miles from the coastline for all states except Texas) receive 27% of all federal royalties from offshore wind development. Beyond 6nm all royalties are retained at the federal government.

projects receiving such grants. This lack of established standards or familiarity with distributed wind on the part of authorities can create an inefficient and costly project development process for installers who need to navigate state, local, and utility regulations as well as educate officials during the process. DWEA published in 2012 a model ordinance and guidelines to lead local governments through the process of adopting wind turbine ordinances for distributed applications [77]. The Interstate Renewable Energy Council issued an update to its Model Interconnection Procedures in April 2013 [232] based on evolving best practices and state rulemakings across the country, particularly in California, Hawaii, and Massachusetts.

State and federal agency compliance is needed for all wind power plants in order to protect historic and cultural resources, wildlife, and wetlands and watercourses. FAA approvals are often necessary as well due to the typical height of larger wind turbines. Additional federal oversight is required for projects that include federal funding, permitting, or are sited on public land. For instance, wind plants proposed for public lands or otherwise subject to federal permitting trigger the National Environmental Policy Act. The Act requires thorough analysis of the impacts of the plant and alternatives to the proposal, as well as public participation in the permitting process. Larger projects may involve a combination of varying land types or organizational jurisdictions, such as an offshore wind project that straddles state and federal waters. Such combined requirements may further complicate the permitting process.

The diversity of requirements, authorities, and decision makers can make it complicated and time-consuming to obtain permission for construction and operation of a wind plant. While federal regulations are standardized at the national level, statutes are applied and enforced through state or regional offices or departments within agencies. Regulations or standards vary to meet local needs and policies. Because of this, there is no uniform permitting process for land-based or offshore wind, and information required for permitting can vary from location to location. The development process can be further complicated by a lack of coordination among local, state, and federal regulators. Wind power has expanded rapidly in the decade leading up to 2014, causing agencies to play catch-up in gaining the understanding and experience to properly evaluate and permit wind plants. As wind development expands into more complex environments, it is expected that permitting processes and considerations for developers and decision-makers will also increase in complexity.

A list of federal regulatory agencies associated with wind is included in Appendix C.

2.8.3 Conclusions

The U.S. wind industry has grown to an installed capacity of more than 61 GW at the end of 2013. Fifteen states had more than 1 GW of wind in operation in 2014, and all but 11 states had some level of utility-scale wind development. Small (distributed) wind systems have been installed in every state. Offshore wind can open new opportunities for utility-scale wind development, including providing access to high-quality wind resources in some densely populated states that cannot accommodate land-based wind development. This growth demonstrates that siting and permitting processes can be navigated successfully. The creation and implementation of appropriate siting practices and continued research to better understand, minimize, and mitigate the environmental impacts of expanded wind deployment can allow continued development while protecting impacted species and addressing competing use concerns. Achieving penetration levels in the *Wind Vision Study Scenario* will require the continued efforts of the industry, agencies, NGOs, and the general public to extract and apply lessons learned from current and future experiences so the industry can grow efficiently and responsibly.

Section 4.6 of the *Wind Vision* roadmap details the wind siting, permitting, and deployment actions necessary to achieve penetration levels comparable to the *Wind Vision Study Scenario,* including:

- Developing impact reduction and mitigation options for competing human use concerns such as radar, aviation, maritime shipping and navigation;
- Developing strategies to minimize and mitigate siting and environmental impacts of wind power plants, including impacts on wildlife;
- Developing information and strategies to mitigate the local impact of wind deployment and operation by continuing to develop and disseminate accurate information to the public on local impacts of wind power deployment and operations;
- Developing clear and consistent regulatory

guidelines for wind development by streamlining regulatory guidelines for responsible project development on federal, state and private lands, as well as in offshore areas; and

- Developing commonly accepted standard siting and risk assessment tools allowing rapid pre-screening of potential development sites.

2.9 Collaboration, Education, and Outreach

A number of government agencies, industry organizations, researchers, academics, NGOs, and collaborative groups are addressing wind-related issues, from permitting and environmental oversight to manufacturing and workforce training. These parties have also enhanced education to help stakeholders understand the role and impact of wind on the energy market, communities, and the environment.

Collaboration by a wide range of stakeholders has improved understanding of impacts, benefits, and deployment hurdles for wind power, and has increased validity and credibility of related research.

Sections 2.9.1 through 2.9.4 provide a brief overview of the types of organizations involved in wind power, including federal and state agencies, NGOs, regional organizations, academia, and outreach groups. Section 2.9.5 discusses recent collaborative efforts, while Section 2.9.6 provides a summary of recent industry activities. International collaboration efforts are discussed in Section 2.9.7.

2.9.1 Federal

DOE is the primary federal agency engaged in wind power education and outreach, with a focus on providing an exchange for unbiased information about wind deployment and its benefits and impacts. There is increased coordination on wind activities across multiple federal agencies, including the U.S. Department of Commerce, DoD, FAA, the U.S. Geological Service, and DOI (which includes BLM, BOEM, the Bureau of Safety and Environmental Enforcement, USFWS, and the U.S. Geological Service). These federal collaborations are based on expanded interest in supporting the appropriate deployment of wind power technologies.

A Navigant report prepared for DOE in 2013 found 70% of stakeholders in DOE's Stakeholder Outreach and Education (WINDExchange and Wind Powering America) initiatives indicated wind power development would have been lower without federal involvement. The report estimates 3.4 GW of wind power capacity are directly attributable to federal stakeholder outreach and educational programs [58].

2.9.2 State

State-level stakeholder engagement and outreach activities vary, from active programs to support plant development to limited formal activities or even active discouragement of wind development. State-level engagement has generally been limited to states with active wind markets, a strong need to expand wind deployment, or local wind champions. Since the early 2000s, state-level wind outreach efforts have been executed through four primary organizations: respective state energy offices, typically funded through state appropriations or DOE grants; wind-focused trade organizations; state university research or student-led outreach programs; and wind or environmental NGOs including the Wind Working Groups formed through DOE funding. In some states, multiple organizations may work simultaneously. Project developers also undertake outreach activities for specific projects, sometimes in a statewide context.

Educational organizations, including universities and community colleges, are also increasingly active in wind power outreach and stakeholder engagement at the state and community levels. Through activities such as Wind for Schools, AWEA student chapters, active faculty, and other wind or sustainable energy-focused student groups, faculty and students are becoming more involved in public engagement even outside of their research. Faculty at these organizations also typically have knowledge of local wind markets. AWEA and DOE maintain a list of educational organizations active in wind power.

2.9.3 NGO Activities

An increasing number of NGOs advocate for wind power through legislative, regulatory, or market barrier removal efforts. Some support wind power development directly, while others recognize wind power as having a role in achieving other objectives relevant to their organization, such as protecting wildlife, reducing carbon emissions, or promoting local economic development. Types of NGOs engaged in wind power activities include trade organizations, wildlife advocates, clean energy proponents, environmental organizations, organized labor groups, public health organizations, and farmers' organizations. Each NGO brings a unique point of view, level of expertise, and network of influence, which helps enhance overall understanding. The decade prior to 2014 has also seen the initiation of NGOs working to reduce the use of wind power by highlighting potential negative impacts of wind development.

2.9.4 Regional Organizations

As the installed capacity of wind technology increases and wind energy becomes more economically viable, regional organizations from a wide range of stakeholder sectors have embraced expanded appropriate wind energy deployment and are providing valuable support in the ongoing effort to educate decision-makers and other community stakeholders. These regional organizations can be comprised of stakeholders from many sectors, including but not limited to businesses, government agencies (including elected officials), environmental and other non-profit groups, rural and agricultural groups (including landowners), and academic institutions. These organizations work with stakeholders to gather and communicate accurate information about wind power, often to help identify and reduce or mitigate actual and perceived impacts.

Regional organizations exist across the United States, even in regions with limited current deployment of wind power. One example of a new regional organization is the Southeastern Wind Coalition, which works to advance the land-based and offshore wind development by building informational bridges between the wind industry, public, other regional organizations and governmental officials. Regional organizations communicate information through scientific literature, social and earned media, and public events, often with support from federal partners.

2.9.5 Collaborative Efforts

Stakeholders have increasingly employed collaborative efforts to approach some of the most pressing challenges to wind power development. This collaboration pools the resources of industry, conservationists, policy makers, and other interested stakeholders to develop innovative solutions. Work by collaborative groups has shifted from the basic sharing of information and best practices to active engagement aimed at solving specific problems.

Collaborative groups working to resolve issues that can limit wider deployment of wind power include:

- The American Wind Wildlife Institute (*www.awwi.org*, see *Environmental Impacts of Wind Deployment* in Section 2.8.1);
- The Bats and Wind Energy Cooperative (*www.batsandwind.org*, see *Environmental Impacts of Wind Deployment* in Section 2.8.1);
- The National Wind Coordinating Collaborative (*www.nationalwind.org*, see *Environmental Impacts of Wind Deployment* in Section 2.8.1), facilitated by AWWI; and
- The Utility Variable-Generation Integration Group (*http://www.uvig.org*, see Section 2.7.5)

2.9.6 Industry Activities

Industry trade associations continue to address siting issues for land-based and distributed wind. As previously discussed, AWEA and DWEA have developed best practices for wind power deployment [231, 77], and the 2011 project development siting guide developed by the Canadian Wind Energy Association demonstrates efforts to ensure successful development of wind through with comprehensive community engagement. These organizations have also done extensive work in stakeholder engagement, outreach, and education at the national, regional, state, and grassroots levels. AWEA and DWEA have standing committees that meet regularly to discuss and address siting challenges. This includes supporting and participating in studies of avian and bat impacts and mitigation approaches, developing sound reduction technology and control algorithms, and working with federal regulators to appropriately deploy wind technologies.

Increasing interest in offshore wind and federal efforts to develop a related permitting process have brought stakeholder concerns to the forefront and expanded industry-focused engagement efforts. Offshore engagement efforts have occurred primarily at the state or local level and have focused on specific projects like Cape Wind. AWEA and several regional organizations are the primary industry organizations addressing offshore wind stakeholder engagement.

2.9.7 International Collaboration

With 28 member countries at the end of 2013,[98] the IEA is the primary organization coordinating international wind-related activities in stakeholder outreach and education. IEA Wind Task 28 was founded in 2010 to consider social acceptance of wind power, and IEA Wind Task 34 started in 2014 to help expand international collaboration on the environmental impacts of land and offshore based wind systems. This international exchange on acceptance issues has proven valuable for those engaged in the work, as well as for government administrators, the research community, IEA Wind members, and wind industry in the respective countries. Other international informational projects are conducted by many European nations and the European Union. The International Renewable Energy Agency, a consortium of more than 130 countries, has initiated efforts to expand the acceptance of all renewable energy technologies, including wind. The Global Wind Energy Council also acts internationally, to consolidate and communicate industry viewpoints, provide information on the benefits and impacts of wind, conduct authoritative research and policy analysis, and support wider international dialogue about appropriate wind deployment.

2.9.8 Conclusions

Collaboration by a wide range of stakeholders has improved understanding of the impacts, benefits, and deployment hurdles for wind power, and has increased validity and credibility of related research. Continued collaboration, education, and outreach will be required to achieve the deployment levels in the *Wind Vision Study Scenario*. Section 4.7 of the *Wind Vision* roadmap details important collaboration, education, and outreach actions related to these efforts. These actions include providing information on wind power impacts and benefits and increasing public understanding of broader societal impacts of wind power, including economic impacts, reduced emissions of GHGs and air pollutants, less water use, and greater energy diversity. Additional actions include fostering international exchange and collaboration on technology research and development; standards and certifications; and best practices in siting, operations, repowering, and decommissioning.

98. *www.iea.org/countries/membercountries/*

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Chapter 2

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Wind Vision: A New Era for
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