Enabling Wind Power Nationwide

May 2015

U.S. DEPARTMENT OF ENERGY

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Executive Summary

Today, wind energy provides nearly 5% of the nation's total electricity generation. With 65 gigawatts (GW) deployed, utility-scale installations in 39 states, and wind power generation exceeding 12% in 11 of those states, wind is a demonstrated clean, affordable electricity resource for the nation. Research and industry experience indicate that wind can be deployed at higher levels while maintaining grid reliability.

Leveraging this experience, the U.S. Department of Energy's (DOE's) Wind and Water Power Technologies Office has evaluated the potential for wind power to generate electricity in all 50 states. DOE analyzed the potential for expanding use of wind nationwide, concluding:

1. The United States has vast wind resources across all 50 states. Continued advancements in turbine technology–including those that enable higher hub heights, larger rotors, and improved energy capture–can access the stronger and more consistent wind resources typically found at greater heights above ground level They also enable wind to be a true nationwide economic resource;
2. Advancements in wind technologies have already yielded broad cost-competitive deployment in locations with high wind speeds. Market trends and technological innovations are increasingly unlocking cost-effective wind in regions with more moderate wind resources;
3. Based on an advanced turbine concept and assuming hub heights of 110 meters (m) (which are already in wide commercial deployment in Germany and other European countries), the technical potential for wind deployment is estimated to grow to 4.3 million square kilometers, a 54% increase compared to current technology with 80-m hub heights. By pursuing hub heights of 140 m, the technical potential for wind deployment is estimated to grow to 4.6 million square kilometers, a 67% increase compared to current technology with 80-m hub heights (Figure ES-1). The geographic distribution for this expanded wind technical resource would include new regions such as the Southeast, as well as increasing the already cost-effective areas where wind power is currently installed; and
4. Improvements in siting practices have contributed to the deployment of 65 gigawatts (GW) in cumulative installed wind capacity (as of 2014). Pursuing more moderate resource quality sites can and should be done in coordination with the broad stakeholder community for wind to coexist with the environment and federal and state agency missions.

This report analyzes and quantifies the geographic expansion that could be enabled by accessing higher above ground heights for wind turbines and considers the means by which this new potential could be responsibly developed. This report describes the current state of wind technology and transportation considerations, and details future technology pathways for technical innovation in towers, rotors, drivetrains, and component transport and installation. As wind turbines become larger, with taller towers and longer blades, transportation logistics become increasingly complex. For example, the height of bridges limits the diameter of towers that can be transported by truck. Innovations to address these challenges include on-site manufacturing, modular components, and new materials and designs for larger systems.

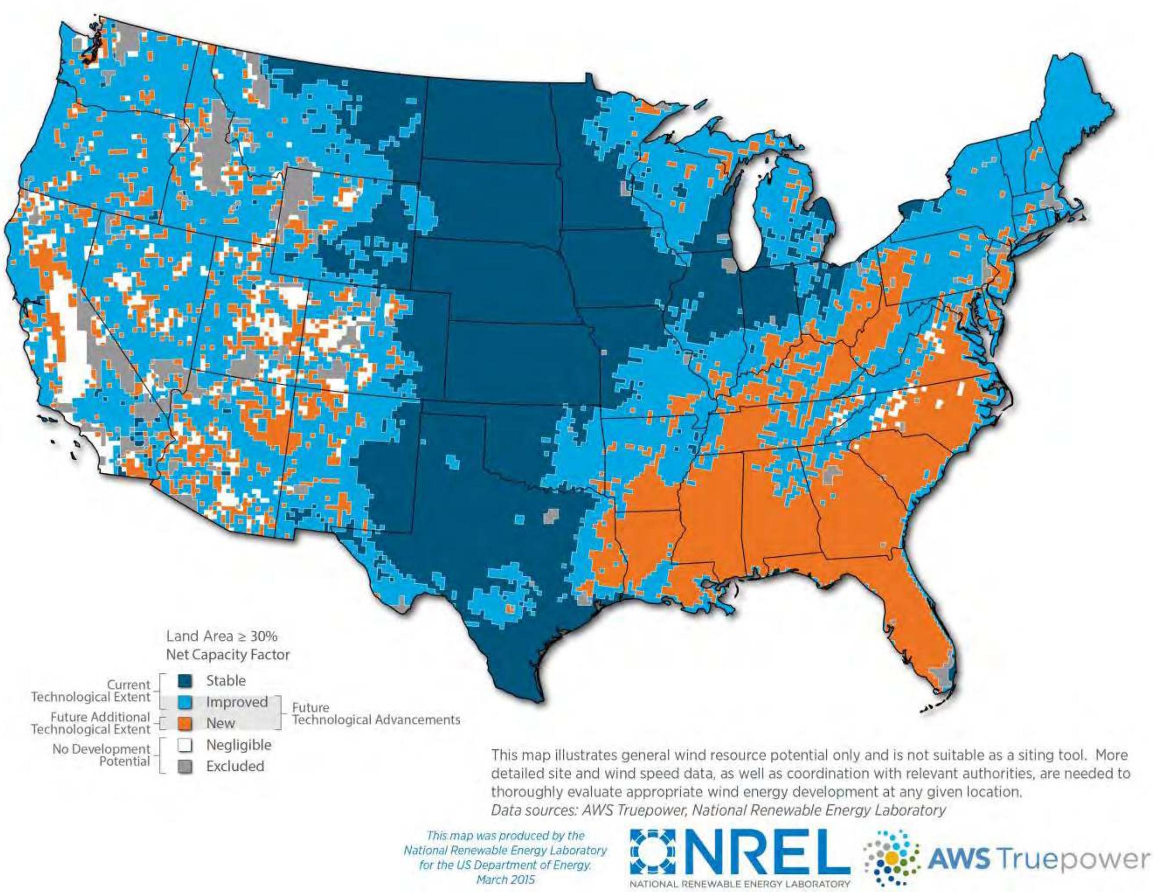
As wind deployment reaches new heights and new regions, additional environmental and human use factors will need to be considered and addressed. This includes the potential for new or additional interactions with wildlife such as birds and bats, as well as effects on their habitats. Additionally, impacts related to human use concerns, such as civilian and military radars, must be also evaluated. Continued research and development, as well as federal, state and local inter-agency coordination, on potential impacts and options for mitigation and resolution are required to ensure responsible deployment.

Several federal agencies have activities currently underway that will support efforts to enable -wind power nationwide. For instance, the Federal Aviation Administration (FAA) is creating lighting guidelines for wind turbines with total heights above 500 feet. In addition, the DOE has recently announced Funding Opportunity Announcements targeting innovative research and development solutions addressing taller towers and larger rotors.

Pursuing higher hub heights can truly enable wind to be deployed across all 50 states. As can be seen in DOE's report, *Wind Vision: A New Era for Wind Power in the United States*

(DOE 2015)[1], there are significant economic and societal benefits that come from wind energy. The *Wind Vision* report calculated the economic and societal value for future wind scenarios, and included economic calculations as well as quantification of societal impacts, such as greenhouse gases (GHGs), pollutants and water use. The report found that wind delivered a wide range of societal benefits, such as reductions in GHG emissions and water consumption. Central estimates for the value of GHG benefits in the *Wind Vision Study Scenario* analysis were $125 billion through 2030, air pollutant reductions were $42 billion through 2030, and water consumption reductions were 173 billion gallons per year in 2030. In addition, wind is estimated to support 375,000 jobs in 2030 and $1.8 billion in local tax and lease revenues in 2030.

The deployment of taller wind turbines (already prevalent in Germany with average hub heights at 116 m) will expand U.S. land area available for wind deployment by 54%. Further innovation and increasing heights to 140 m will increase that further to 67%. Innovations addressing the technical and economic challenges, as well as the environmental and human use considerations, are critical to realize the nation’s full wind power potential and value for all 50 states as described in this report.



Note: Dark blue coloring identifies high quality wind resource areas that see no change in available land area meeting the 30% minimum net capacity factor threshold with technology advancement because the entire area is capable of achieving this threshold today. Light blue coloring identifies land area that meets the capacity factor threshold today but sees an increase in the proportion of the area able to achieve this threshold as a result of turbine and hub height improvements. Orange coloring identifies new land area able to achieve the minimum 30% net capacity factor level as a result of turbine and hub height improvements.

Figure ES-1. Land area achieving a minimum 30% net capacity factor by grid cell, based on current technology, larger rotor designs and a 140-m hub height

Source: DOE 2015

[1] Available for download at energy.gov/windvision

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1.0 Future Opportunity Scenarios for Wind Energy

U.S. wind deployment can provide substantial value as part of the U.S. electricity generation portfolio. The U.S. Department of Energy (DOE) analyzed and quantified the economic impacts of wind deployment in the DOE report, *Wind Vision: A New Era for Wind Power in the United States* (DOE 2015),[2] which explored a future U.S. wind deployment scenario of 10% wind electricity by 2020, 20% by 2030, and 35% by 2050. DOE quantified the economic benefits and impacts of wind deployment in terms of greenhouse gas (GHG) reductions, pollution reductions (sulfur dioxide [SO_2], nitrogen oxide [NOx], and fine particulates), water use and withdrawal reductions, price stability economic impacts, land use, local land lease, local tax generation, U.S. jobs and U.S. manufacturing impacts.

1.1. Wind Vision Identifies Potential for Significant National Benefits

The 2015 DOE report, *Wind Vision: A New Era for Wind Power in the United States* (DOE 2015), found that through continued innovation in technology and markets, the deployment of incremental U.S. wind power generation in a portfolio of domestic, low-carbon, low-pollutant power generation solutions is both feasible and economically compelling. This report, *Enabling Wind Power Nationwide,* focuses on the timeframe through 2030, taking into consideration the current state of U.S. wind turbine technology and likely timeframe to realize the technology innovations that will enable higher hub heights, larger rotors and improved energy capture. U.S. wind power could provide 20% of U.S. power requirements with high grid reliability by 2030, but concerted actions by all stakeholders are required to achieve this level of deployment. Three elements critical for enabling further wind deployment emerge from DOE's *Wind Vision* collaborative analysis and roadmap development:

- Technology improvements to further reduce wind power costs, allowing deployment in new geographic regions of the nation;
- Transmission expansion to access high quality wind resources and enhance operation of the electric power system; and
- Energy market pricing that recognizes the value of low carbon, low emissions power sources.

Analytical Framework of the Wind Vision

The *Wind Vision* effort analyzed a *Study Scenario* of wind power supplying 10% of national end-use electricity demand by 2020, 20% by 2030, and 35% by 2050. This *Study Scenario* provides a framework for conducting detailed quantitative impact analyses. It starts with current U.S. manufacturing capacity and applies central projections for variables such as wind power costs, fossil fuel costs, and energy demand to arrive at a credible projected pathway for the existing industry for purposes of calculating potential social and economic benefits. The *Wind Vision* report additionally modeled a *Baseline Scenario* and a *Business-as-Usual (BAU) Scenario* as summarized in Table 1-1. Several *BAU Scenario* sensitivity analyses on variations of the central projection parameters substantiated the *Wind Vision Study Scenario* as a viable scenario for the U.S. wind industry.

Impacts of the Wind Vision Study Scenario

The *Wind Vision* report indicates that under a scenario in which wind energy grows to serve 10% of the nation's electricity demand by 2020 and 20% by 2030, wind power is estimated to provide annual benefits of $9 billion in 2020 and $30 billion in 2030 (2013$) from air pollution reductions and greenhouse gas emissions reductions. These environmental benefits are bolstered by consumer savings for natural gas purchases outside the electric sector, wind investment derived jobs totaling 330,000-426,000 by 2030, and direct land-lease and property tax payments totaling hundreds of millions of dollars annually by 2020 and billions of dollars annually by 2030.

These benefits are observed to fully offset the expected costs to electricity consumers from increased wind deployment through 2020 and 2030 as existing plants retire and fossil fuel prices trend upward, relative to a scenario that holds wind power at 2013 levels. These conclusions hold under nearly all conditions considered in the Wind Vision, including high and low estimates of costs and benefits (Figure 1-1 and Figure 1-2). Such benefits highlight the broad-based economic value that wind power provides the nation.

[2] The *Wind Vision Report* represents a collaboration of the U.S. Department of Energy (DOE) with industry, electric power system operators, environmental stewardship organizations, federal government agencies, research institutions and laboratories, and siting and permitting stakeholder groups to inform actions and options in the development of incremental U.S. wind power. Available for download at http://energy.gov/windvision.

Table 1-1. Analytical Framework of the *Wind Vision*

Analytical Framework of the *Wind Vision*	
Wind Vision Study Scenario	The *Wind Vision Study Scenario*, or *Study Scenario,* applies a scenario of 10% of the nation's end-use demand served by wind by 2020, 20% by 2030, and 35% by 2050. It is the primary analysis scenario for which costs, benefits, and other impacts are assessed. The *Study Scenario* comprises a range of cases spanning plausible variations from central values of wind power and fossil fuel costs. The specific *Study Scenario* case based on those central values is called the *Central Study Scenario*.
Baseline Scenario	The *Baseline Scenario* applies a constraint of no additional wind capacity after 2013 (wind capacity fixed at 61 GW through 2050). It is the primary reference case to support comparisons of costs, benefits, and other impacts against the *Study Scenario*.
Business-as-Usual Scenario	The *Business-as-Usual (BAU) Scenario* does not predetermine a wind future trajectory, but instead models wind deployment under policy conditions current on January 1, 2014. The *BAU Scenario* uses demand and cost inputs from the Energy Information Administration's Annual Energy Outlook 2014.

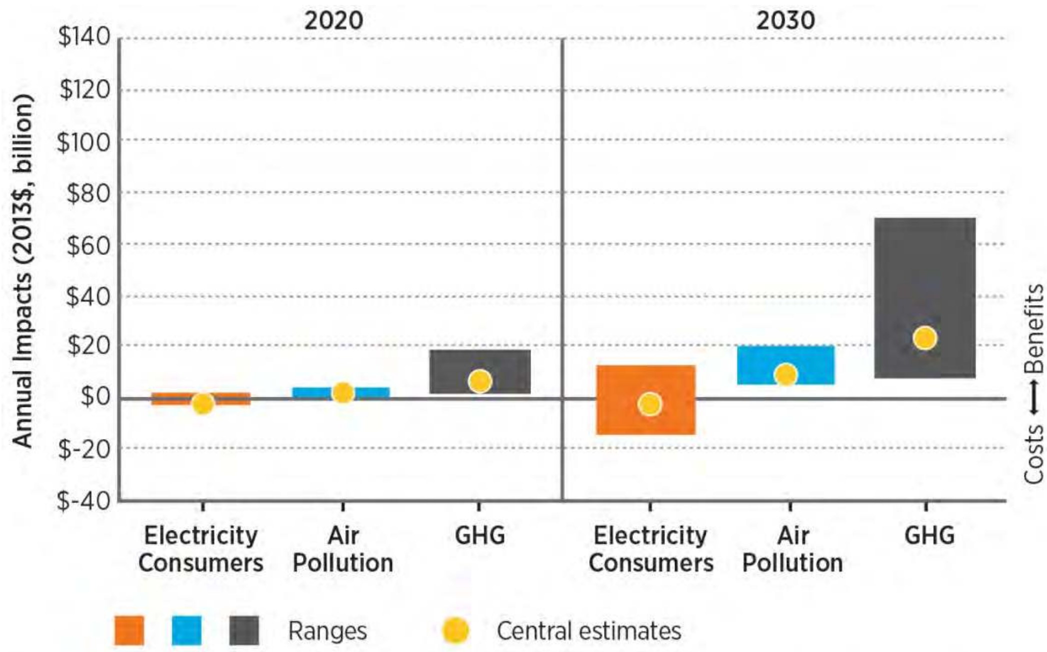
Opportunity to Expand Wind Power into New U.S. Geographic Regions

Realizing the full benefits described above requires continued innovation, research and development (R&D). Expansion of wind power as detailed in the *Wind Vision Study Scenario* occurs as offshore turbines are deployed in coastal states and advancements in land-based turbine technology emerge to support lower-wind speed areas such as the southeastern United States. Under the scenario in which wind power supplies 10% of national electricity demand in 2020 and 20% by 2030, wind power is extended to more than 40 states by 2020 and nearly all states (49) by 2030. Twenty-five states are observed to have 1 gigawatt (GW) of operating wind power capacity by 2020 and 37 states exceed the 1 GW threshold by 2030 (DOE 2015). Achieving broad-based geographic viability supports economic deployment of wind energy, and also reduces the demand for new transmission infrastructure and provides increased opportunities to place wind in locations where there may be fewer intersections with environmental and human-based concerns.

System Costs	Benefits		
$	H_2O	GHG	Air Pollution
Annual (2030) Electricity Consumer Costs	**Annual (2030) Water Savings**	**Cumulative GHG savings through 2030**	**Cumulative Air Pollution savings through 2030**
$1.5 billion in savings	173 billion gallon saved	$125 billion in savings	$42 billion in savings
0.3% reduction	11% less consumption	8% less GHGs emitted	6,200 lives saved

Note: Annual impacts represent the impact for 2030 only. Cumulative impacts are for the period 2013-2030 and are reported on a Net Present Value basis. Both annual and cumulative impacts reflect the difference in impacts between the DOE *Wind Vision Central Study Scenario* and the *Baseline Scenario*. Results reported here reflect central estimates within a range. Financial results are reported in 2013$ except where otherwise noted. Electricity consumer costs include capital, fuel, and operations and maintenance for transmission and generation of all technologies modeled, but exclude consideration of estimated benefits (e.g., GHG emissions).

Figure 1-1. Wind Vision Study Scenario costs and benefits in 2030
Source: DOE 2015



Note: Results represent the annual incremental costs or benefits (impacts) of the *Study Scenario* relative to the *Baseline Scenario*. Central estimates are based on *Central Study Scenario* modeling assumptions. The electricity consumers costs range reflects incremental expenditures (including capital, fuel, and operations and maintenance for transmission and generation of all technologies modeled) across a series of sensitivity scenarios. Air pollution and GHG estimates are based on the *Central Study Scenario* only, with ranges derived from the methods applied and detailed in the full report.

Figure 1-2. Estimated value of electric sector and emissions impacts resulting from a scenario in which wind supplies 20% of the nation's electricity demand by 2030, compared with a scenario in which wind capacity is held at current levels through 2030

Source: DOE 2015

1.2. Report Structure

This report details the means by which this geographic expansion of wind power could occur, discusses the impacts these technical advancements could have in terms of creating new opportunities for wind deployment, and highlights new or additional land use and wildlife considerations for the industry that could emerge with an expanded geographic footprint.

- Chapter 2 highlights the accomplishments of the wind power industry to date including recent technological trends.
- Chapter 3 describes how wind technology R&D contributes to both a lower cost of energy and an expansion of the available land area able to support commercial wind deployment.
- Chapter 4 details the expanded geographic wind resource potential associated with continued technology advancement.
- Chapter 5 details global technology trends and technical challenges and opportunities, including transportation constraints, which must be addressed to allow continued expansion of wind in new geographies and at higher hub heights.
- Chapter 6 discusses environmental and human-based considerations—including birds, bats, competing uses and public acceptance—that will need to be considered as wind deployment expands.
- Chapter 7 concludes the report, with a discussion of next steps and required actions. In particular, pursuing higher hub heights and larger rotors (lower specific power)[3] must be done responsibly and in coordination with broad stakeholder community. Technologies deployed must preserve both environmental stewardship and coexist with the mission of multiple agencies.

[3] As described in more detail in section 3.4, increasing the rotor swept area (square meters) by increasing rotor size while holding turbine generator capacity (Watts) constant reduces the specific power (W/m^2) of the wind turbine. The larger the rotor swept area, the more wind energy can be captured.

2.0 U.S. Wind Power – Progress to Date

As of 2015, installed wind power is a significant contributor to the nation's electricity generation portfolio, with more than 65 gigawatts (GW) installed across 39 states supplying 4.9% of the nation's electricity demand in 2014 (EIA 2015). The nation has a vast wind resource across many states, both land-based and offshore. The technical potential for land-based wind energy for the contiguous United States is estimated to be 12,000 GW of generating capacity at 100-meter (m) hub height (NREL 2010a)—assuming a net capacity factor of at least 26%; and the technical potential for offshore wind energy is estimated to be 4,150 GW (NREL 2010b). These resources combined are greater than 10 times current total U.S. electricity consumption.[4] While not all of this technical resource potential will realistically be developed, it represents a vast opportunity.

U.S. wind generation substantially contributes to reducing power sector environmental impacts. In 2013, greenhouse gas (GHG) emissions were reduced by 115 billion metric tonnes; sulfur dioxide (SO_2) emissions were reduced by 157,000 metric tonnes; nitrogen oxide (NOx) emissions were reduced by 97,000 metric tonnes; and water consumption was reduced by 36 billion gallons (DOE 2015) due to wind power. U.S. wind is also supporting an average of 73,000 total jobs over the period 2010–2014 and more than 500 U.S. manufacturing facilities operating in 43 states (AWEA 2015).

Cumulative installed U.S. wind capacity has increased to a level more than ten times capacity installed ten years ago. Technology advancements have yielded cost-competitive deployment in high wind speed locations, making utility-scale wind power a cost-effective source of low-emissions power generation throughout much of the nation. Wind costs have decreased by more than 90% and wind rotor sizes have doubled since the 1980s. This trend of increased wind efficiency leading to lower costs, corresponding to larger turbines with increased rotor sizes, is projected to continue to drive increased benefits at continuing lower costs.

2.1 Investment, Capacity, and Generation Trends

Since the late 1990s, wind energy deployment has grown exponentially. Installed global wind power capacity has increased from 6 GW in 1996 to more than 365 GW as of year-end 2014 (GWEC 2015). For the period of 2004–2013, annual global investment in wind technology has grown from an estimated $14 billion to more than $80 billion (UNEP 2013, UNEP 2014). Wind contributions to the global electricity supply have mirrored these trends and, as of 2013, wind provided an estimated 3.4% of global generation (Wiser and Bolinger 2014).

In the United States, installed wind power capacity has grown from 1.4 GW in 1996 to more than 65 GW as of year-end 2014 (Figure 2-1). Cumulative investment from the early 1980s through 2013 totals more than $125 billion (Wiser and Bolinger 2014).

The geographic extent of U.S. wind power has also expanded. As of year-end 2000, there were 16 states with installed wind power capacity, and more than half of these had less than 25 megawatts (MW). By 2008, 35 states had utility-scale wind power operating within their boundaries and, by 2013, there were 39 states with operating utility-scale wind power (Figure 2-2).

2.2 Benefits of Wind Power

Deployment of wind power results in an array of co-benefits. Principal benefits include local economic development opportunities for rural project host communities as well as equipment and hardware manufacturers around the country; support for power sector reductions in historically regulated pollutants including SO_2, NOx, and particulate matter (a precursor to ozone formation); and reductions in water use and carbon dioxide (CO_2) emissions. Figure 2-3 highlights a sample of estimated environmental benefits realized in 2013 as a function of wind power generation.

In terms of economic development impacts through year-end 2013, the wind supply chain consisted of an estimated 560 domestic facilities operating in more than 43 states. These facilities contributed to an estimated 2012 domestic content level of approximately 60%, calculated as the share of total investment costs (hardware and construction)[5] sourced domestically (Wiser and Bolinger 2014). An estimated 50,000 jobs were supported by on-site and direct wind industry supply chain investments in 2013 (AWEA 2014), and an average of 73,000 total jobs were supported over the period 2010–2014 (AWEA 2015).

[4] U.S. 2014 electricity end use of 3,831 Terawatt-hours (TWh) (EIA Monthly Energy Review, December 2014) is equivalent to 13.1 quadrillion BTU. The identified U.S. wind potential of over 15,000 GW is roughly 140 quadrillion BTU.

[5] From components in categories tracked by trade codes

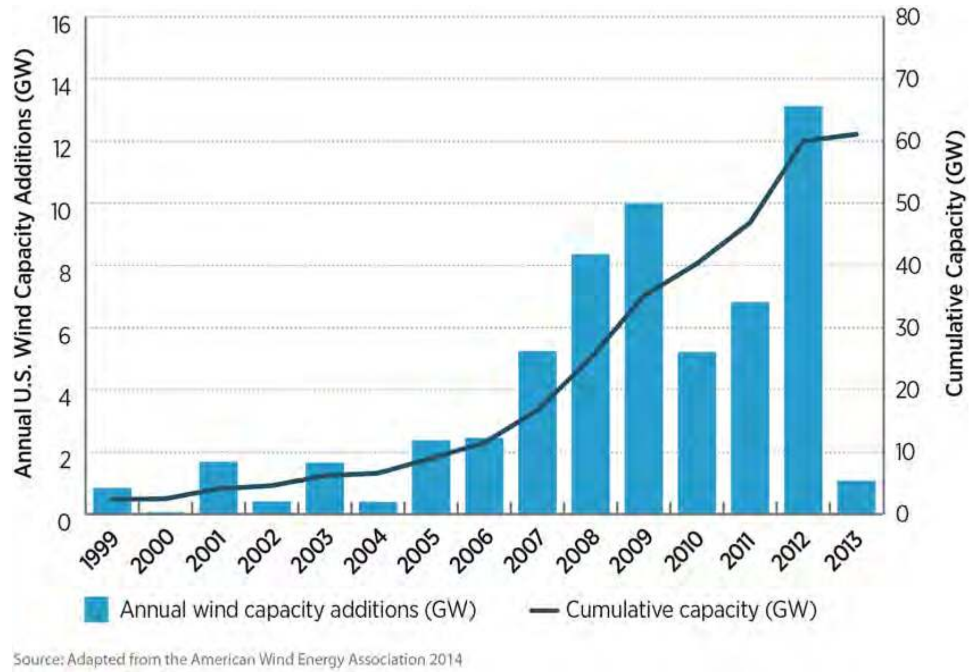


Figure 2-1. Installed wind power capacity trends in the United States
Source: DOE 2015

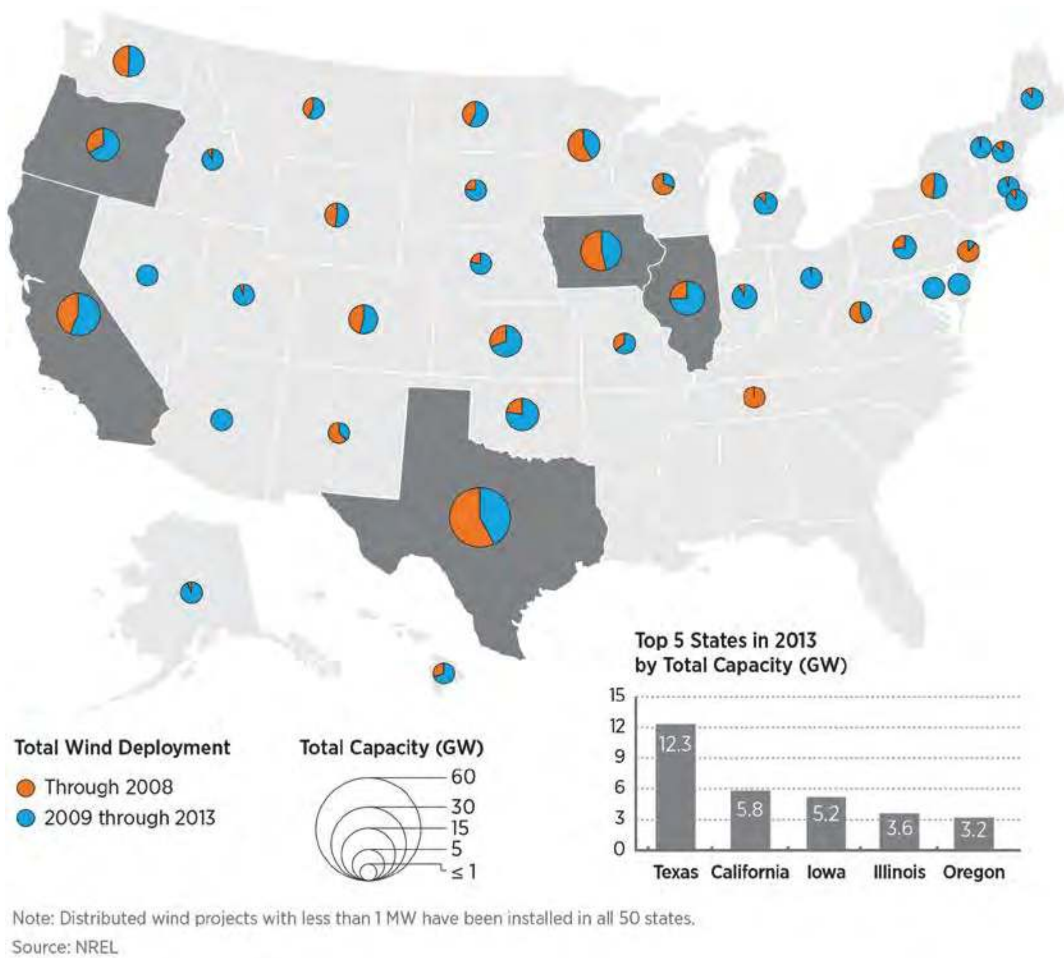


Figure 2-2. Geographic footprint of U S wind power capacity 2008 and 2013
Source: DOE 2015

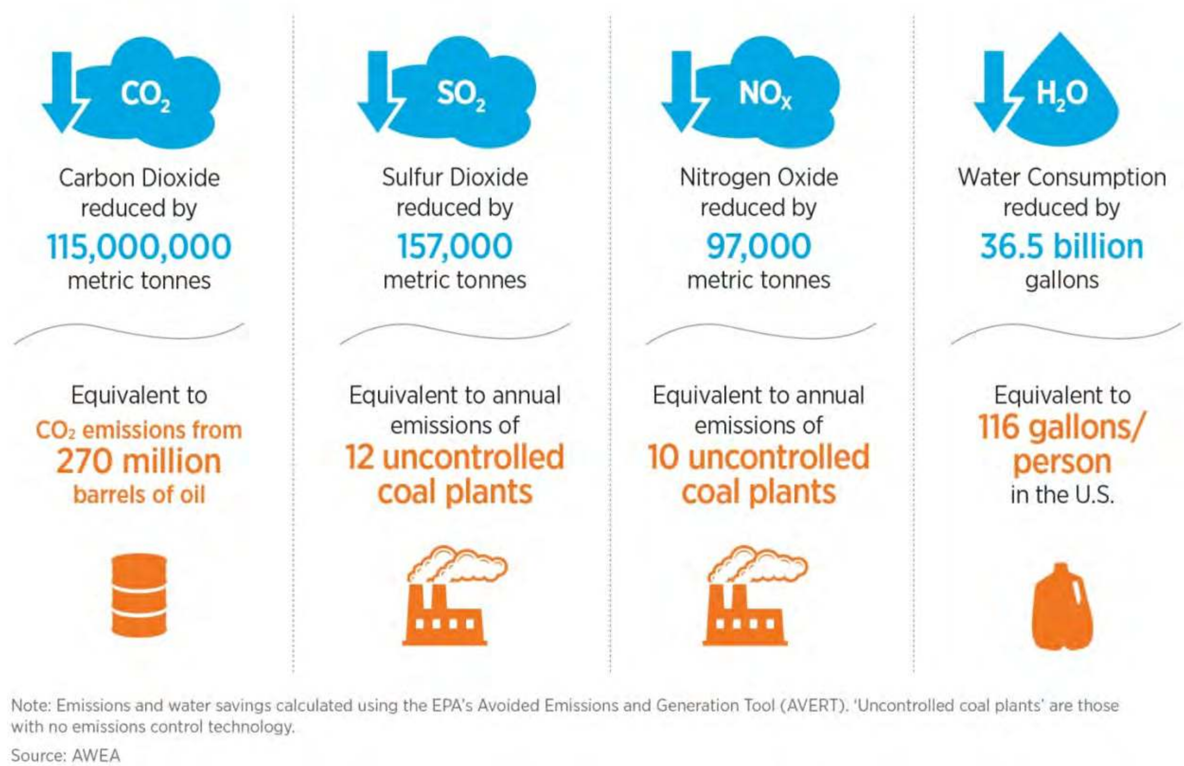


Figure 2-3. Estimated reductions in emissions and water use from wind generation in 2013
Source: DOE 2015

Brown et al. (2012) quantified empirical impacts in counties hosting wind power projects that were installed between 2000 and 2008 and found an average increase in county-level personal income of $11,000/MW of installed capacity and an average increase in county-level employment of approximately 0.5 jobs/MW.

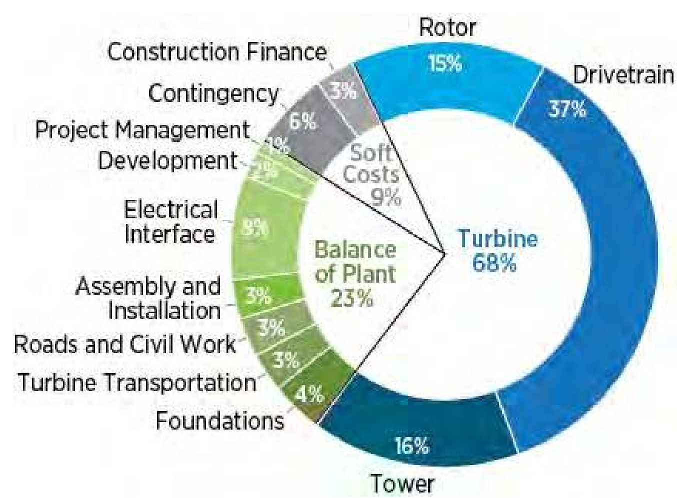


Figure 2-4. Components of installed capital cost for a land-based, utility-scale reference wind turbine
Source: DOE 2015

2.3 Wind Power Cost Trends

Growth in wind power investment and capacity has supported substantial cost reductions. Total installed project capital costs include not only the turbine, comprising the rotor, drivetrain, and tower, but also the balance of system costs.[6] Balance of system costs comprise balance of plant and "soft" costs (Figure 2-4).[7] Focusing first on U.S. installed costs, capacity weighted averages have been reduced from levels exceeding $5,000/kilowatt (kW) to levels of $1,630/kW in 2013 (Figure 2-5).

[6] 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

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

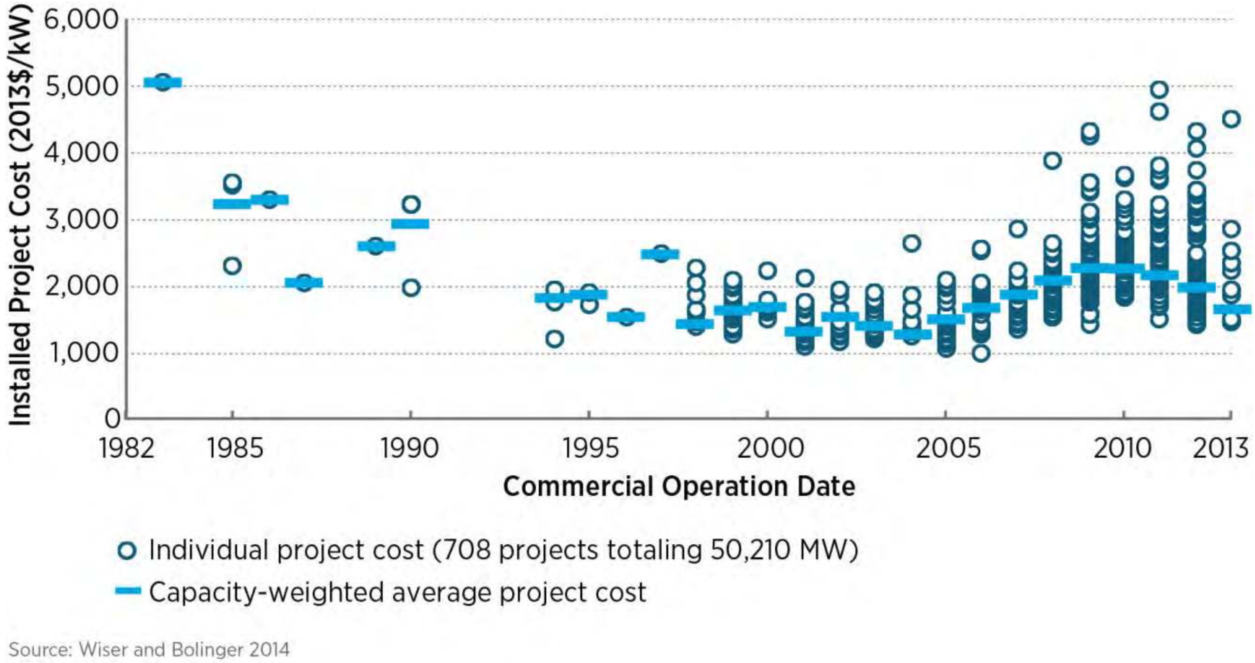


Figure 2-5. Trends in wind power installed project costs
Source: Wiser and Bolinger 2014

Turning to estimates of U.S. levelized cost of electricity (LCOE) (excluding the value of the Production Tax Credit) and projects operating in good to excellent wind resource sites, LCOE has declined at an average rate of 7% since 1980. After a slight upward trend between 2003 and 2009, LCOE estimates fell by nearly 40% for the period of 2009–2013 (Figure 2-6).

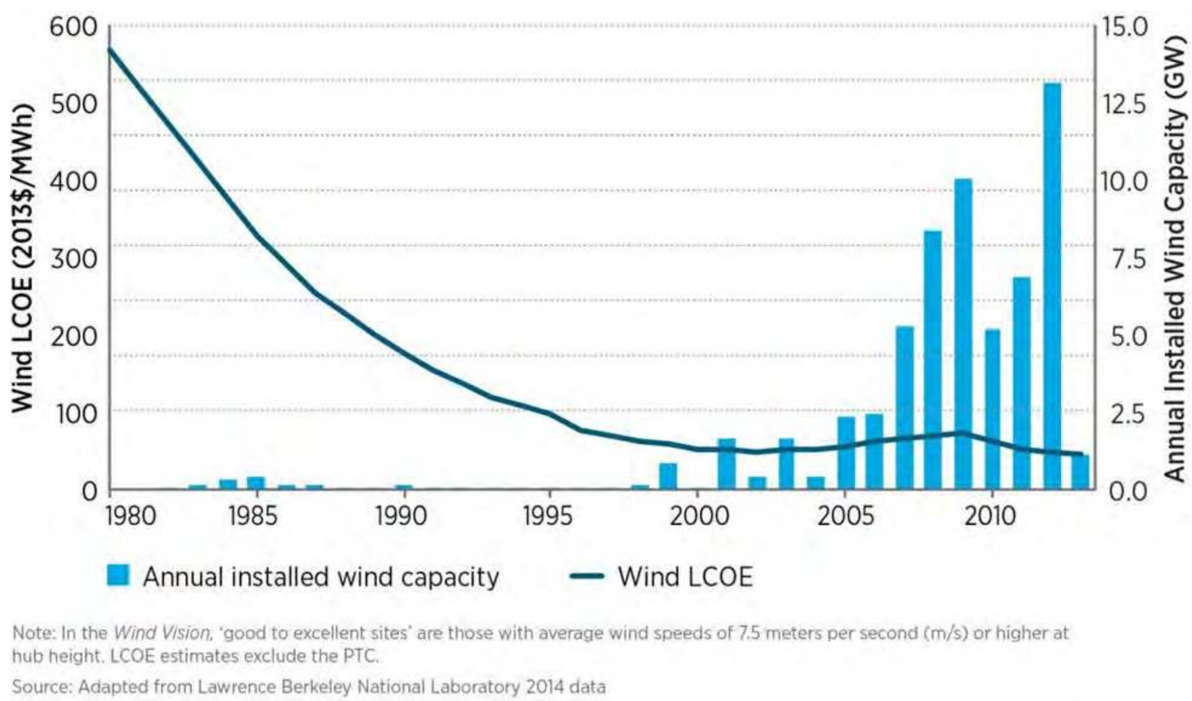


Figure 2-6. Trends of average U.S. wind energy LCOE for good to excellent resource sites and annual U.S. wind power capacity installations
Source: DOE 2015

Wind power costs are expected to continue to fall, albeit at a slower annual rate than what has been accomplished given the relative maturity of the technology. Analysis conducted by Lantz et al. (2012) and updated by DOE (2015) suggests that, under business-as-usual conditions, wind power costs could be reduced an additional 9% by 2020 and 16% by 2030, while more aggressive efforts to lower costs could achieve an additional 24% reduction in LCOE by 2020 and 33% by 2030.

2.4 Wind Power Technology Trends

Wind technology has undergone a measurable change in terms of turbine and plant-level productivity, driving reductions in the cost of wind power. Productivity changes have resulted from a combination of increased rotor diameter and higher hub heights (Figure 2-7).[8]

Blade design improvements have enabled rotor-driven impacts, allowing for expanded rotor size with relatively few impacts throughout the rest of the turbine and limited incremental material costs.

These trends represent a continuation of historical turbine scaling observed in the industry since the 1980s. In addition to increased productivity per dollar invested in plant hardware, turbine scaling also offers the potential for reductions in dollars invested per MW based on reduced balance of system costs in the form of fewer roads, fewer turbine pads, and fewer pieces to assemble (Chapman et al. 2012). Reducing overall counts of needed parts will improve continuous wind plant power generation and reliability, which will further lower the cost of energy (Chapman et al. 2012).

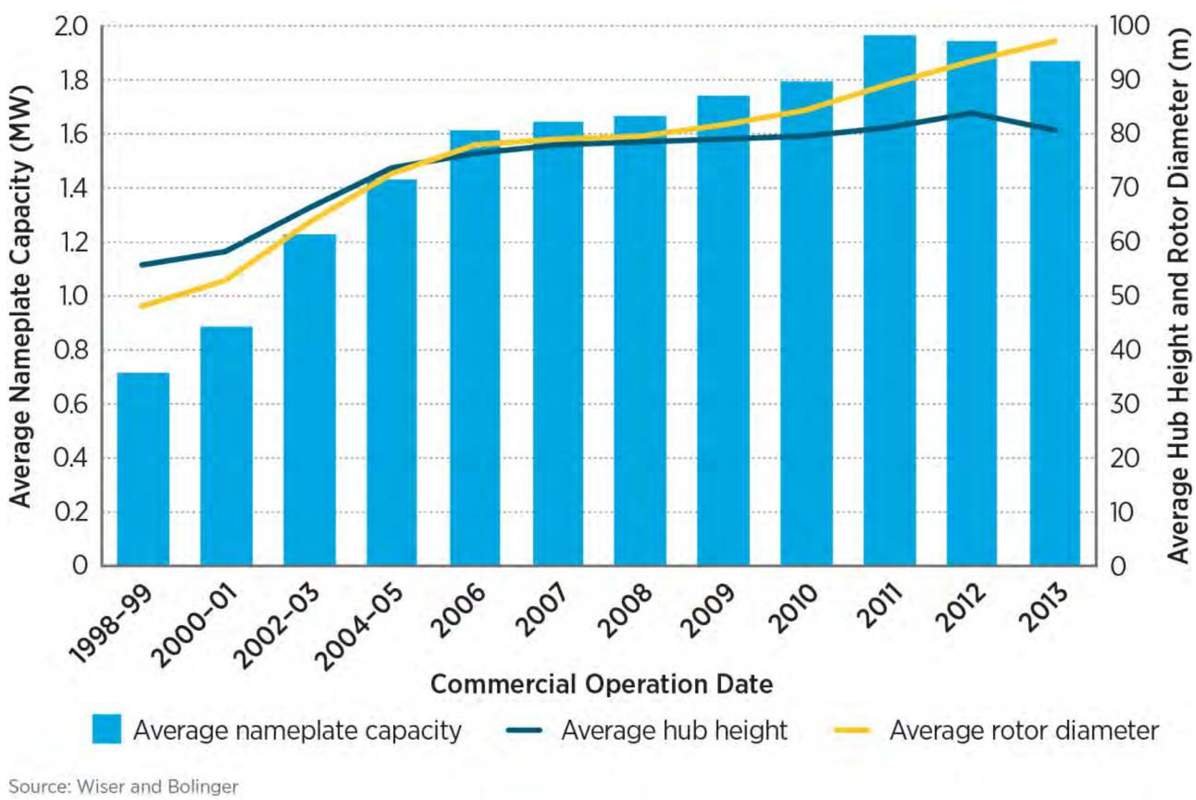


Figure 2-7. Historical trends in U.S. wind turbine rotor diameter, hub height, and nameplate capacity
Source: Wiser and Bolinger 2014

[8]Wiser and Bolinger (2014) illustrate that average rotor diameter has increased from approximately 80 m in 2008 to nearly 97 m in 2013. This represents an increase in rotor diameter of just over 20% and an increase in rotor swept area of nearly 50%.

3.0 Understanding Wind Energy

Improving wind systems to achieve reduced costs for both lower wind speeds and higher wind speeds at higher levels above the ground is essential to creating economical wind solutions in all 50 states. DOE, in conjunction with industry and academia, is exploring the science and engineering of these next-generation systems.

This chapter summarizes the physics and science of wind, including wind turbine power production and capacity factor, the wind turbine power curve (including cut-in and cut-out speeds and shifting of the power curve to achieve higher generation at lower wind speeds), wind resource by region, and the atmospheric boundary layer. Understanding the trade-offs between theoretical performance (as discussed in this chapter) and the technical challenges of engineering cost-efficient wind systems, including increased rotor sizes and higher tower heights, and addressing corresponding transport and logistic challenges of larger wind systems (as discussed in Chapter 5), is crucial to effectively deploying economical wind solutions in all 50 states.

3.1 Economic Considerations

The annual energy production of a wind plant depends on the wind resource characteristics at a given site and the power generation characteristics of the wind turbine chosen for that site. In addition, wind is a free but variable resource. This chapter provides an overview of key wind energy concepts necessary to understand the potential benefits and challenges of accessing winds at higher hub heights. The economics of wind energy, often discussed in terms of levelized cost of energy (LCOE) depend on: (1) the initial capital costs, including the cost of the turbines, balance of system costs, transportation and installation costs; (2) the recurring annual operations and maintenance (O&M) expenses; and (3) the annual energy production (AEP), which is net energy collected by the plant which ultimately drives the annual revenue generated by the wind plant. For wind energy to be economical, the wind plant must maximize AEP while limiting capital costs and O&M expenses below a certain level. The objective of accessing winds at higher hub heights is to increase AEP relative to the increases in initial capital costs or O&M.

Due to the variable nature of wind, the AEP and resulting LCOE are highly site-dependent, even if identical turbines are used at each site. To determine AEP at a given site, the wind resource characteristics and the turbine power curve (discussed in more detail below) must be considered together.

3.2 Wind Turbine Energy Production

A wind turbine is a mechanical device that converts the kinetic energy available in the wind into electrical energy. While several different designs of wind turbines have existed throughout history, the most common and successful design is the upwind horizontal axis wind turbine, which uses a three-bladed rotor to extract energy from the wind. As the blades rotate, the rotor sweeps an area normal to the direction of the wind flow in form of a circular disk, known as the rotor swept area. The kinetic energy flowing through the rotor swept area is the net energy available for conversion by the wind turbine. The total kinetic energy per unit time, or power, in the wind can be expressed as

$$\text{Power}_{\text{wind}} = 0.5\ \times \rho\ \times A\ \times U^3$$

where ρ is the ambient air density, A is the area swept by the rotor, and U is the wind speed that is assumed uniform across the rotor disk. Based on this equation, a number of observations can be made about the relationships among these variables. First, the power extracted by the turbine is proportional to the swept area of the rotor and varies as the cube of the wind speed. The actual power generated by the turbine, however, depends on the aerodynamic and mechanical efficiency of the turbine. Based on theoretical aerodynamics considerations, Betz's law (Manwell et al. 2010) sets a maximum upper limit on the aerodynamic efficiency or Coefficient of Power (Cp) of an ideal rotor at 59%. In practice, most turbines extract around 48–50% of the available wind power after accounting for aerodynamic and mechanical losses and other considerations.

$$\text{Power}_{\text{turbine}} = 0.5\ \times \rho\ \times A\ \times U^3 \times\ Cp$$

Figure 3-1 shows a typical power curve for a modern wind turbine, the power extracted by rotor as a function of wind speed. The turbine requires a minimum wind speed, called the *cut-in wind speed*, before it is able to extract power from the wind. This speed is usually based on generator design limits. At speeds above the cut-in wind speed, power generation increases as the cube of the wind speed. The cubic relationship means that the rotor produces eight times more power for each doubling of wind speed; this continues until the rotor hits the rated power. Finally, at higher wind speeds, machines have a *cut-out wind speed*, where the turbine shuts down to prevent mechanical damage from excessive loads on the turbine components at high wind speeds.

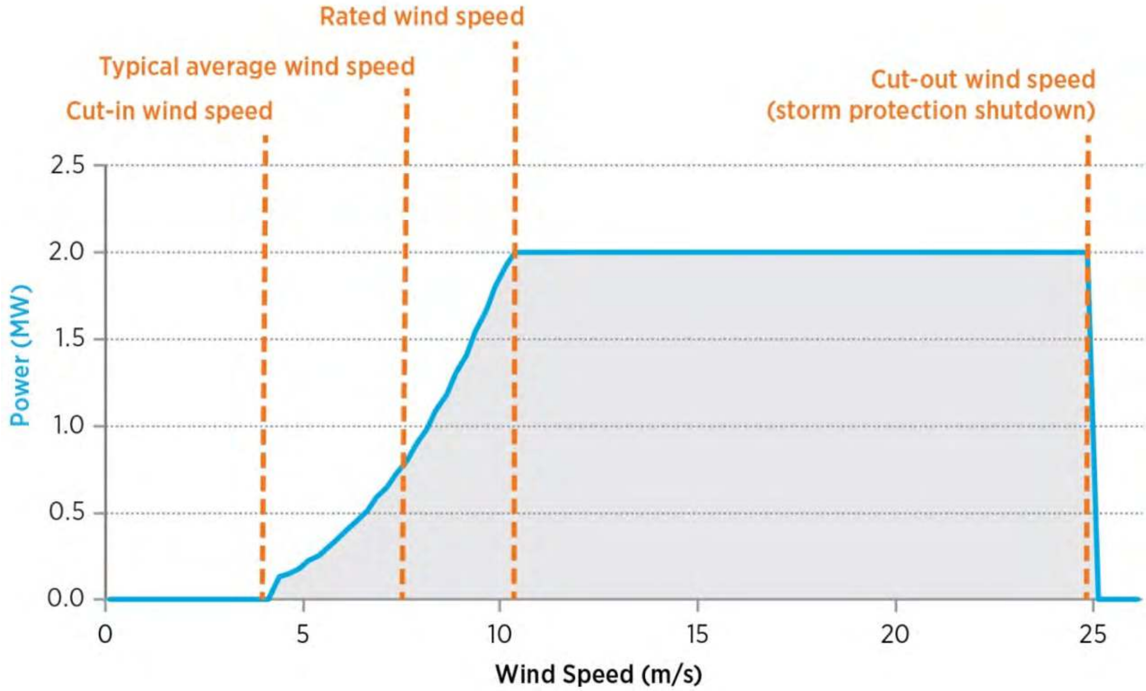


Figure 3-1. Typical power curve for a modern wind turbine
Source: NREL

3.3 Nature of the Wind Resource

Global Drivers of the Wind Resource

As noted, analyzing the economic viability of a wind plant is complicated by the variable nature of the wind resource. The amount of wind energy varies significantly depending on the geographic location of the wind plant, the height of the turbines above ground, the time of the year, and the time of day. The amount of potential wind energy available at a wind plant is influenced by global wind patterns. These global patterns are created as a result of the combination of two factors: the uneven solar heating of the Earth's surface; and the Coriolis forces created as a result of the Earth's rotation—forces that influence the movement of air masses.

Regional Influences on the Wind Resource

On regional scales, the wind speed at a given height above ground is affected by topography, vegetation, and the presence and size of man-made obstacles that affect movement of the wind. Topographical variations such as hills or mountains can create local increases in wind speed, just as sheltered valleys and mountain leewards can result in reduced wind speed. Vegetation and obstacles also affect the characteristics of the wind locally, both decreasing the wind speed and increasing the turbulence. These effects can be seen in Figure 3-2, which shows the average wind speeds observed across the United States at 80-m height. Because higher wind speeds generally mean increased AEP and lower LCOE for a given wind turbine, a significant portion of the installed U.S. wind is concentrated in the Midwest, where the highest wind speeds are observed.

Understanding the Atmospheric Boundary Layer

For wind to be a truly national resource and contribute 20% or more of the nation's energy needs by 2030, future installations will need to include low wind speed sites such as the southeastern United States. To understand what technology pathways would make wind energy economically viable in these sites, it is necessary to understand the nature of wind within the earth's Atmospheric Boundary Layer (ABL).

The ABL is the lowest layer of air within the troposphere that is in contact with the Earth's surface. This region is relatively shallow, extending 1-3 km above the Earth's surface, and its physical characteristics are influenced by the intensity of solar heating (convection), local terrain conditions, presence of vegetation and man-made obstacles, and latitude.

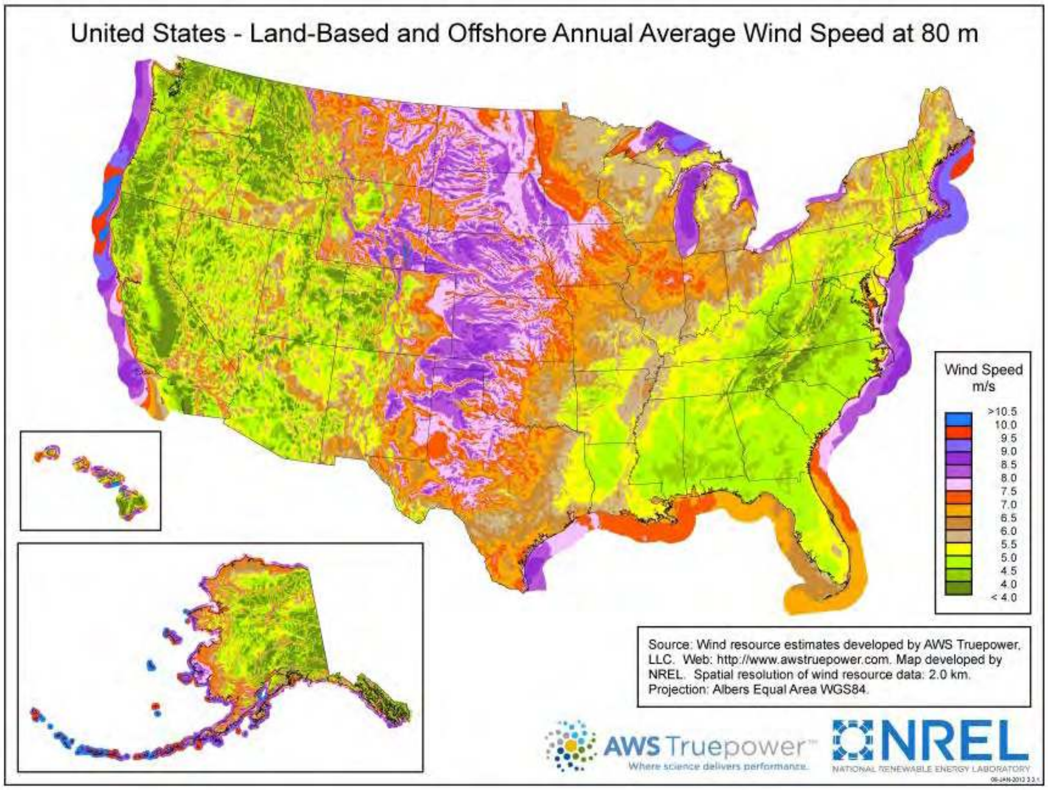


Figure 3-2. Average wind speed across United States at 80 m (≈ 262 ft)
Source: DOE 2015

Even at a given location, the conditions within ABL vary considerably on several time scales: annual variations where the wind resource shows differences on a year-to-year basis, monthly variations due to seasonal changes, and diurnal (daily) variations. Thus, at any given moment, wind turbines encounter a complex, three-dimensional wind profile, as depicted in Figure 3-3. Since wind turbines operate within the ABL, understanding the nature of ABL is critical for effective, reliable wind engineering.

For wind energy applications, the ABL is most often characterized in terms of temperature profile, wind speed profile, wind shear, turbulent intensity, and wind veer.[9] The variability observed in the wind profile over short durations is due to the turbulence and is often characterized by turbulent intensity. This variability has two important implications: the power output of the wind turbine is not constant and varies as a function of time, and structural loads fluctuate and can impact wind turbine reliability.

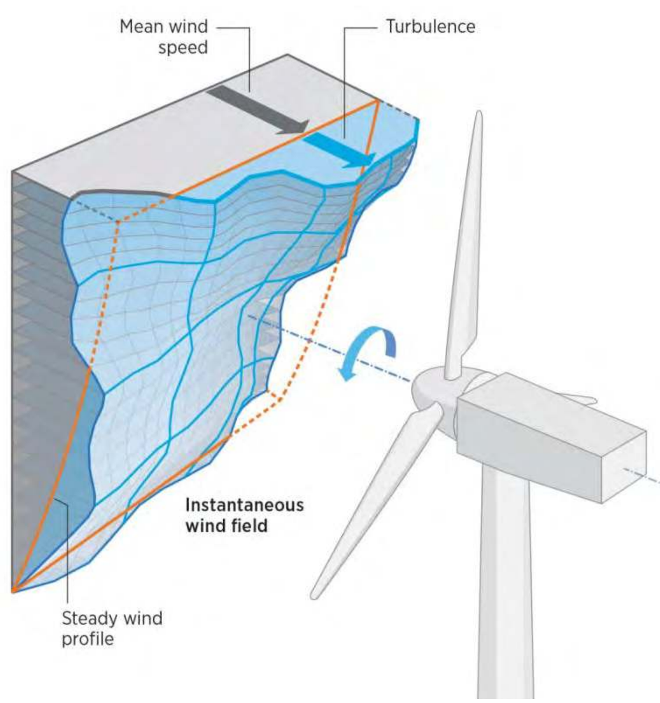


Figure 3-3. Conceptual depiction of wind profile impinging on a wind turbine
Source: NREL

[9] Wind veer is a measure of any shift in the direction of the wind in the horizontal plane with increasing height above ground.

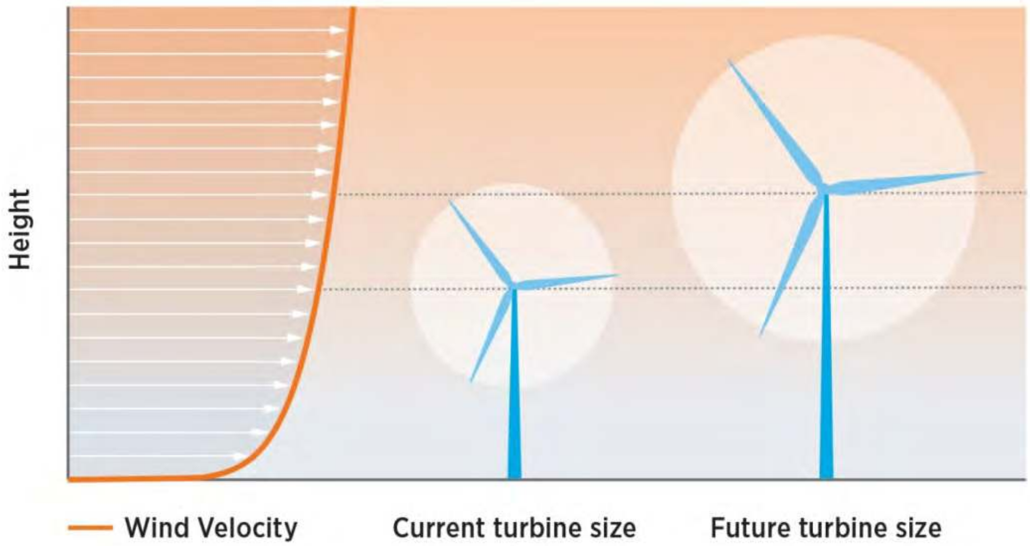


Figure 3-4. Representative wind atmospheric boundary layer velocity profile with two turbines of different heights
Source: NREL

Due to friction, the terrain causes the wind layers closest to the ground to move more slowly than the wind layers above it, thereby resulting in the typical mean ABL velocity profile as shown by Figure 3-4. This variation of speed as a function of height is called the wind shear. Because of wind shear effects, the bottommost portion of the rotor will extract less energy from the wind, as compared to the topmost section. This has two implications: First, at a given hub height, the energy extraction by the rotor decreases in proportion to increases in wind shear, compared to a rotor operating at constant wind speed across its entire swept area. Second, increasing the hub height will allow the rotor to capture more energy for the same rated power and swept area. Simple analysis suggests that gains of 20-45% are possible by increasing the height of the towers from 80 m to 140 m in moderate-to-high shear sites. This is because the power varies as the cube of the wind speed, and even modest increases in wind speed (as a function of height) contribute to the power captured.

3.4 Annual Energy Production and Capacity Factor

Due to the variable nature of wind, the power output from a wind turbine varies with time. When evaluating the economics of wind, it is often useful to look at the annual energy production (AEP) of a wind turbine or a wind power plant. AEP is the net energy produced by the turbine or a plant over the course of a single year. Estimating AEP requires knowledge about the power curve of the turbine and statistical approximation of the site-specific availability of wind at heights of interest. Figure 3-5 shows AEP estimates for a wind turbine which matches the site-specific wind characteristics with the installed wind turbine machine type to determine an expected power generation projection.[10] The wind power curve (grey in Figure 3-5) indicates the power potential of the wind itself. The wind turbine power curve (orange in Figure 3-5) indicates the power generated by the turbine as a function of wind speed. This is used in conjunction with the Weibull curve (NIST 2013), shown in blue in figure 3-5, which provides statistical estimates of the fractional time in a given year when the wind speed is a given value. Weibull curves are site-specific and determined through comprehensive site assessment by the wind plant developer. Together, the power curve and the Weibull distribution of wind estimate the contribution to the AEP at each wind speed, as shown by the green curve in Figure 3-5. The area under the green curve is the net AEP.

Another quantity often used to compare wind plants with conventional fossil power plants is the capacity factor. The capacity factor, or CF, is a measure of the efficiency of the power plant. For wind plants it is defined as

$$CF = \frac{AEP}{Rated\ Power\ \times 8760}$$

[10] The schematic assumes a 2 MW turbine with a 100-m rotor, specific power of 250 W/m^2, IEC wind class 3a and Weibull k factor of two.

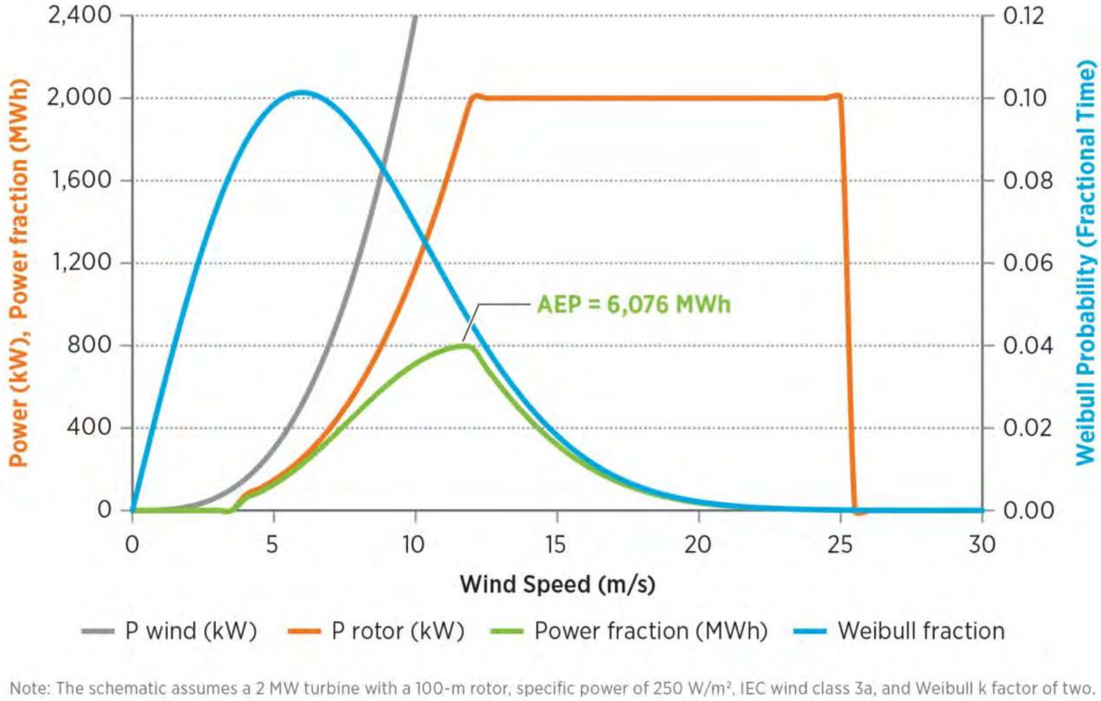


Figure 3-5. Schematic relationship between wind speed, the wind speed distribution (Weibull curve), a typical wind turbine power curve, and the amount of energy produced by the turbine given the wind speed distribution
Source: NREL

For existing technology, the average net capacity factor across the installed U.S. fleet of wind turbines is about 32% (Wiser and Bolinger 2014). This capacity factor includes the effects of many older, less efficient wind turbines still in operation. This is because wind is a variable resource and at speeds below the rated wind speed, the turbine produces less than rated power. Increasing wind plant capacity factor through technology innovation is critical to make wind energy economical and competitive with conventional energy sources. Turbine original equipment manufacturers have focused on increasing capacity factor by reducing rotor specific power,[11] with a goal to make turbines cost effective at low wind speed sites. By lowering the rotor-specific power, i.e., increasing rotor diameter for the same turbine power rating, the machine generates more power at lower wind speeds. This "shifts" the power curve to the left and increases the capacity factor as shown by Figure 3-6.

This increase in capacity factor is often more than sufficient to offset the increased capital costs of a larger rotor and makes wind power economical in low wind speed sites. Technology trends confirm this, with more use of oversized rotors to target low wind speed sites across the United States. Continuing to reduce rotor-specific power, in combination with increasing tower heights, will contribute to lower LCOE so that wind can be installed economically in all 50 states.

[11] Rotor specific power is defined as power per unit area (W/sq. m) and is equal to $P/A = 0.5 * \text{Density} * U^3 * C_P$.

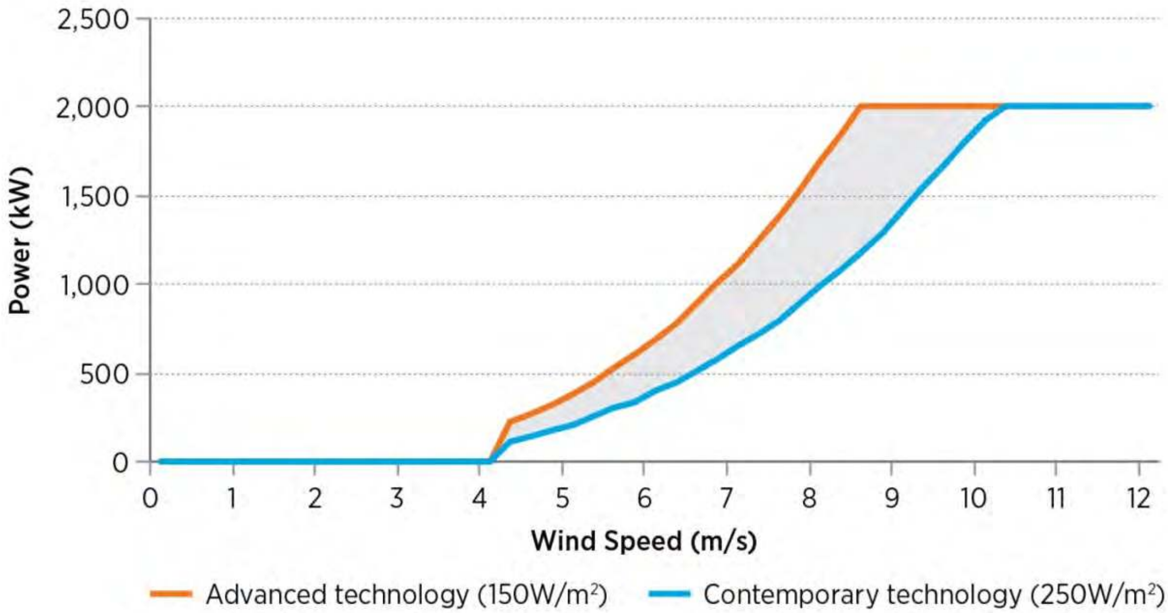


Figure 3-6. Power curve shift in the region between cut-in speed and rated wind speed resulting from use of rotors with lower specific power
Source: NREL

4.0 Expanding Wind Power to all 50 States

Wind technology advancements have consistently lowered the cost of wind energy and expanded the technology's geographic potential. Increased energy production per dollar invested has and can continue to open previously marginal resource areas to development. This has positive benefits to the business community, utility sector, and public with more options in terms of siting wind plants. Moreover, by increasing the amount of land area that can support commercial wind develop-ment, there are greater opportunities for localized benefits including economic development and placement of electricity supply proximate to the end-user, which reduces dependence on new transmission infrastructure. Expanding the amount of land that can support commercial wind development also has the potential to help avoid interactions with sensitive wildlife habitat and conflicts with competing uses (discussed in Chapter 6).

Chapter 4 discusses how continued technological advancement–specifically innovation to achieve higher above ground level hub heights (i.e., taller towers) and greater energy production per unit of installed capacity (i.e., lower specific power)–can enable an increase in the technical potential of wind power.

4.1 Advanced Technology Impacts on Technical Potential

Technical potential typically removes resources limited by high-level geographic constraints including metropolitan areas, lakes and waterways, national parks, designated wilderness areas, and similar protected lands (Chapman et al. 2012, Lopez et al., 2012). The technical potential of wind power has historically used a performance threshold equivalent to a 26% net capacity factor (30% gross capacity factor assuming 15% losses) as a lower bound on the available technical resource potential (Cotrell et al. 2014, Elliot et al. 2010). DOE analysis in 2014 and 2015 applied a 30% net capacity factor threshold (DOE 2014a, DOE 2015). This was done in an effort to better approximate long-term economic opportunity, given historical fleet average net capacity factors of 30–35% and recent performance improvements noted in Chapter 2 and described by Wiser and Bolinger (2014). Changes in technical potential for 2008, 2013, and the future are estimated and reported based on the 30% net capacity factor floor.

Technical Potential in 2008

Technical potential in 2008 is calculated using a representative composite turbine for that era. In this case, the turbine is assumed to have a hub height of 80 meters and a specific power[12] of approximately 400 W/m^2. [13] Wind resource data are consistent with that used by Elliot et al. (2010) and Lopez et al. (2012). These data represent hourly resource data derived from 200-m resolution data aggregated to 20-km^2 grid cells. Map shading shows the amount of potentially developable area within each 20-km cell: the darker the color, the larger the potentially developable area within each cell. Areas that are excluded from development by law, such as wilderness areas and national parks, and other areas unlikely to be developed, such as urban areas and water bodies, have also been excluded. Based on the composite turbine applied to the hourly resource data, technical potential is estimated to be 1,643,000 km^2 (as reflected by land area able to support a net capacity factor of 30% or greater). The geographic distribution and concentration of the potential based on the 2008 composite turbine are shown in Figure 4-1.

Technical Potential in 2013

Wind technology has experienced a significant change in terms of turbine productivity since 2008, with accompanying reductions in the cost of energy. Changes in productivity since 2008 have been achieved primarily through advanced rotors optimized for lower wind speed sites, and have resulted in a new generation of machines with larger rotors and lower specific power. Technical potential based on state-of-the-art machines including low specific power or IEC Class III turbines (210 Watts (W)/m^2) , IEC Class II (300 W/m^2), and IEC Class I (320 W/m^2) machines—all on an 80-m tower and in sites appropriate for their design—is estimated at 2,765,000 km^2.[14] The geographic distribution and concentration for this current technical potential are shown in Figure 4-2.

[12] Specific power is a means of reporting the relative wind turbine rotor to generator size whereby the nameplate capacity of the wind turbine in watts(W) is divided by the swept area of the rotor in square meters (m^2)

[13] This composite machine is further defined as having a 2.0 MW nameplate capacity and an 80 meter rotor diameter, resulting in a specific power of approximately 400 W/m^2.

[14] Rather than using a single composite turbine for the 2013 estimate of technical potential, these results rely on placement of one of three turbine concepts in sites appropriate for their original design and the standards under which the turbine has been certified. A single turbine concept is used for each IEC Class.

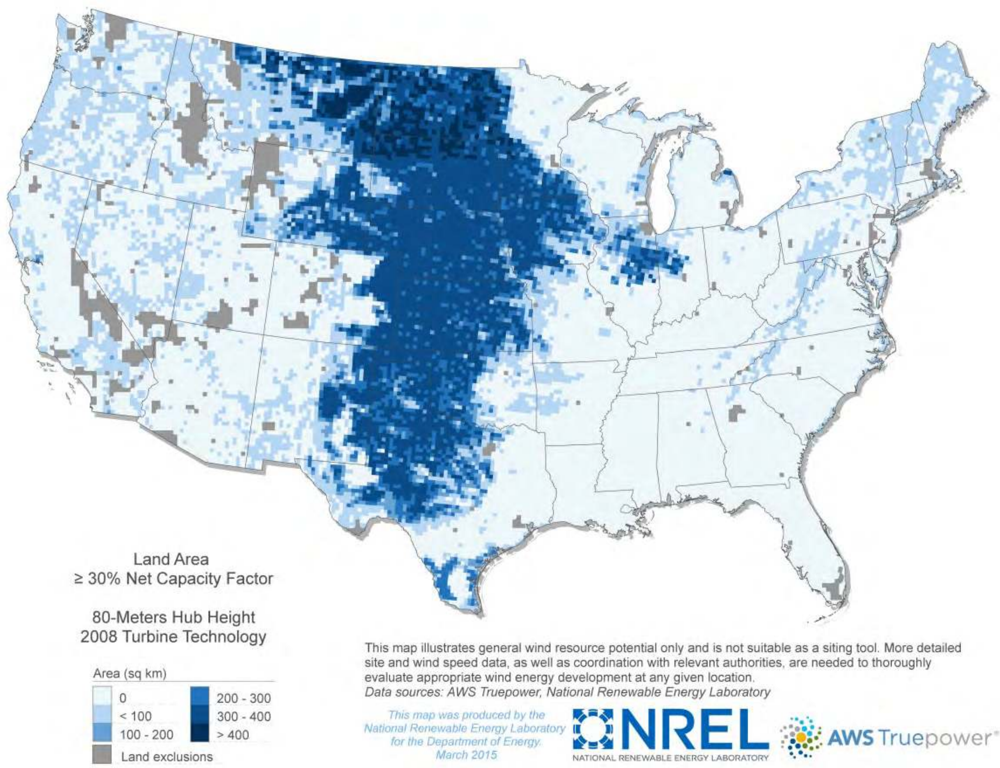


Figure 4-1. Land area achieving a minimum 30% net capacity factor by grid cell, based on 2008 technology
Source: DOE 2015

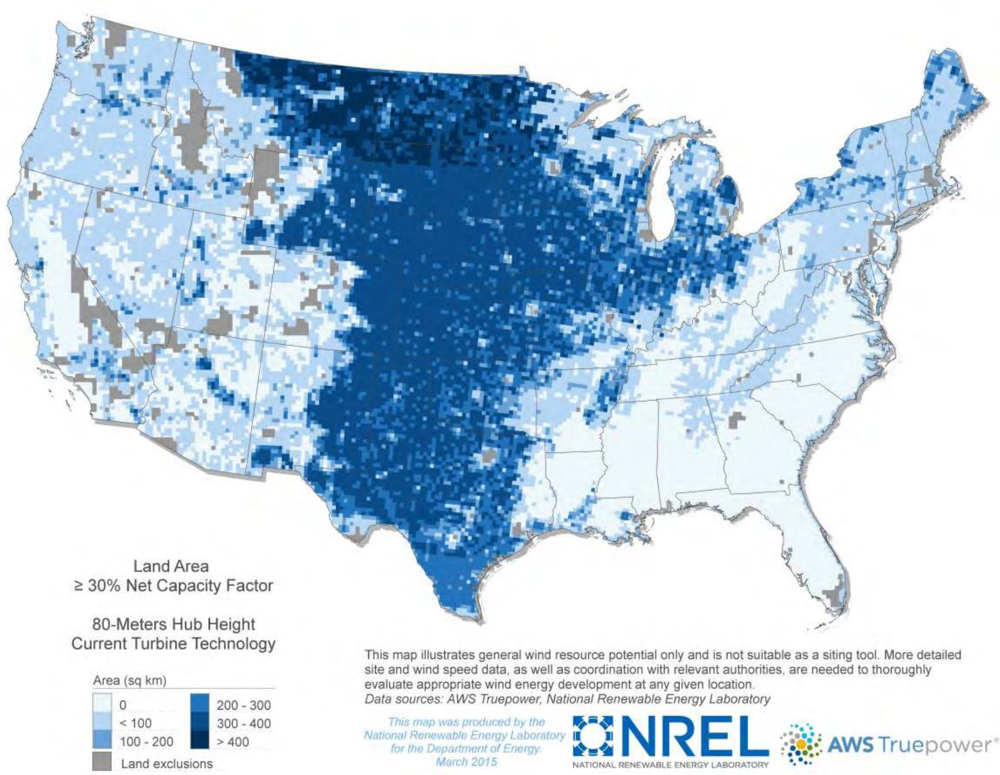


Figure 4-2. Land area achieving a minimum 30% net capacity factor by grid cell, based on 2013 technology
Source: DOE 2015

Based on this estimate, technological advancement has increased technical potential by approximately 68% between 2008 and 2013.

Near-Future Technical Potential

Innovations are underway today that would allow wind turbines to achieve even lower specific power as a function of continued growth in rotor size relative to nameplate capacity. The widespread commercial realization of these technologies in the very near future would allow turbines to increase energy production at wind speeds that occur with the highest frequency, often lower than rated power. Consistent with longer-term historical trends (see section 2); continued tower height increases are also expected.

Increases in tower height would allow the requisite ground clearance to be achieved for large rotor machines. Such increases would also move turbines into higher quality resource conditions, i.e., higher above-ground levels where the wind resource experiences reduced surface disruptions. Such trends are already occurring in Europe, particularly Germany, where average installed tower heights have exceeded 100 m since 2009, with turbine height installations averaging 116 m in 2014 and occasionally even exceeding 140 m (Figure 4-3).[15] Both of these innovation opportunities would support even greater expansion of the U.S. land area able to support a net capacity factor of 30% or greater.

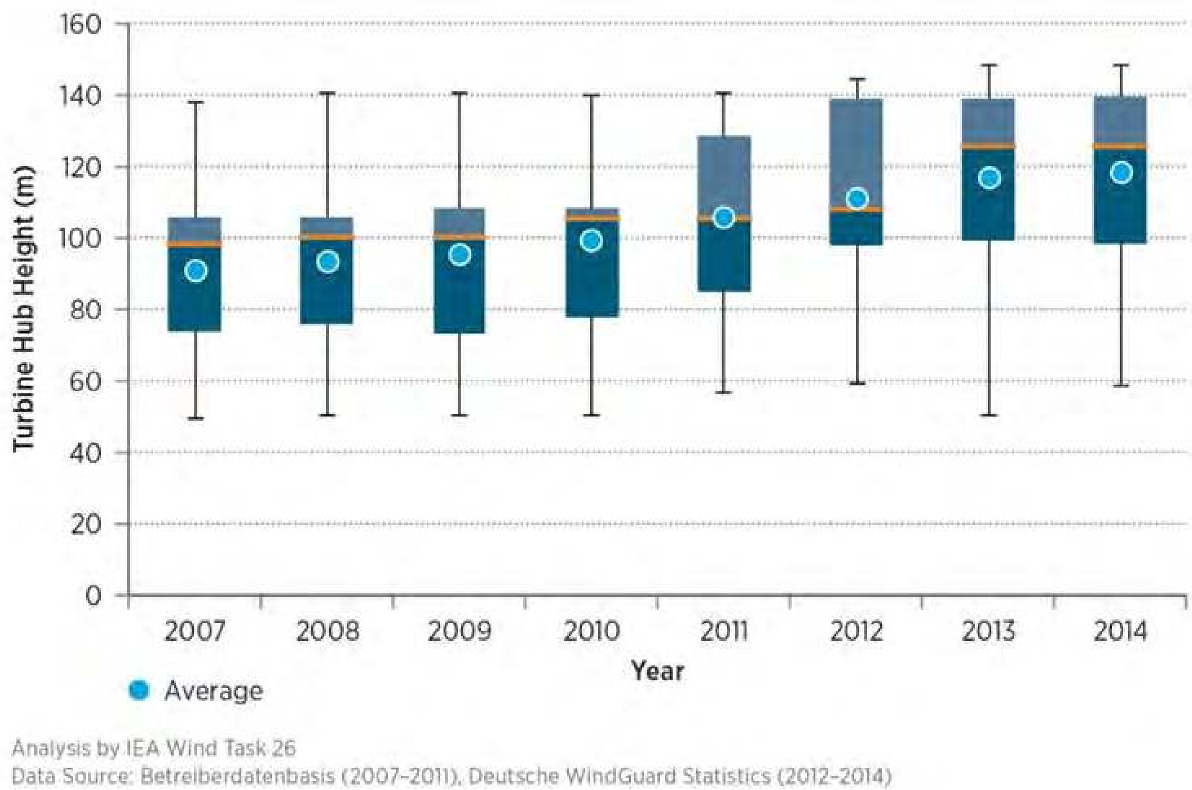


Figure 4-3. Wind turbine hub height trends in Germany from 2007 to 2014
Source: Lüers et al. (forthcoming)

[15] Technology trends in Germany are believed to be partially a function of the relatively poor wind resource quality at lower above-ground level heights and relatively high population density, particularly in relation to regions of the United States in which wind development is occurring. Such trends are also affected by the relative cost and availability of more conventional energy resources, including natural gas, and competing renewable power resources such as solar photovoltaics.

Focusing on the combined impacts of continued reductions in specific power and increased hub heights, this report estimates the technical potential at hub height levels of 110 m and 140 m. These future estimates are calculated using a conceptual wind turbine with a rotor diameter of 124 m (relative to a 2013 U.S. average of 97 m) and a turbine nameplate capacity of 1.8 MW (relative to a 2013 average of 1.87 MW). This results in a turbine with a specific power of approximately 150 W/m^2 (MAKE 2013; Wiser and Bolinger 2014). The conceptual turbine applied here would increase turbine rotor swept area approximately 2.4 times relative to a 2008 turbine with an average rotor diameter of 80 m, and more than 60% relative to the average turbine installed in 2013.

Although such changes are expected to be technically feasible with commercial innovations currently in development and are not expected to trigger key transport or logistics threshold constraints identified in Chapter 5 (MAKE 2013), the economic viability is site dependent. Based on this turbine concept (150 W/m^2) and assuming hub heights of 110 m and 140 m, technical potential is estimated to grow to 4,262,000 km^2 and 4,629,000 km^2, respectively. The geographic distribution and concentration for this expanded technical potential are shown in Figures 4-4 and 4-5. Relative to 2013, placing the conceptual turbine on a 110-m hub would result in an increase in technical potential of about 54%; placing this turbine on a 140-m hub would result in an increase of approximately 67%. Regions primarily affected by this increased technical potential include the Southeast, states bordering the Ohio River Valley, the Great Lakes Region, the Northeast, and portions of the Interior West and Pacific Northwest.

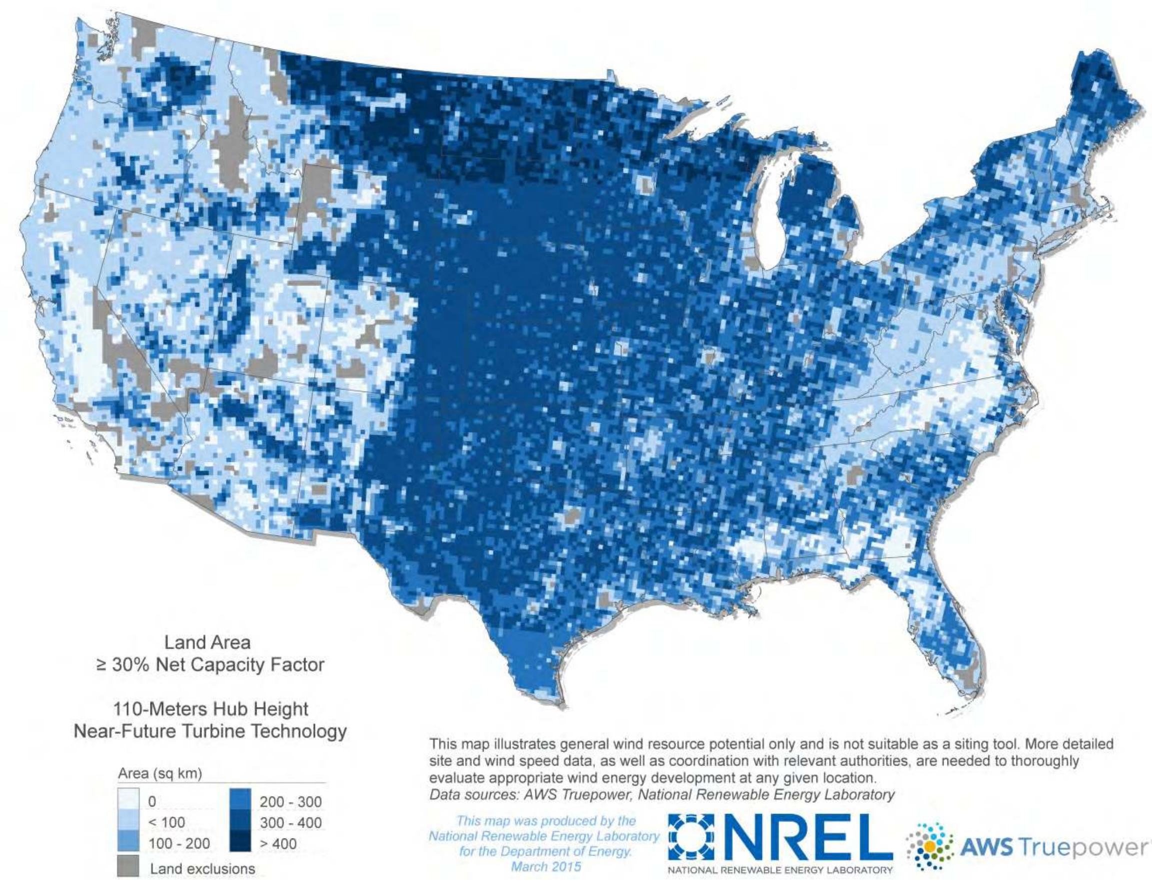


Figure 4-4. Land area achieving a minimum 30% net capacity factor by grid cell, based on lower specific power (150 W/m^2) and a 110-m hub height

Source: DOE 2015

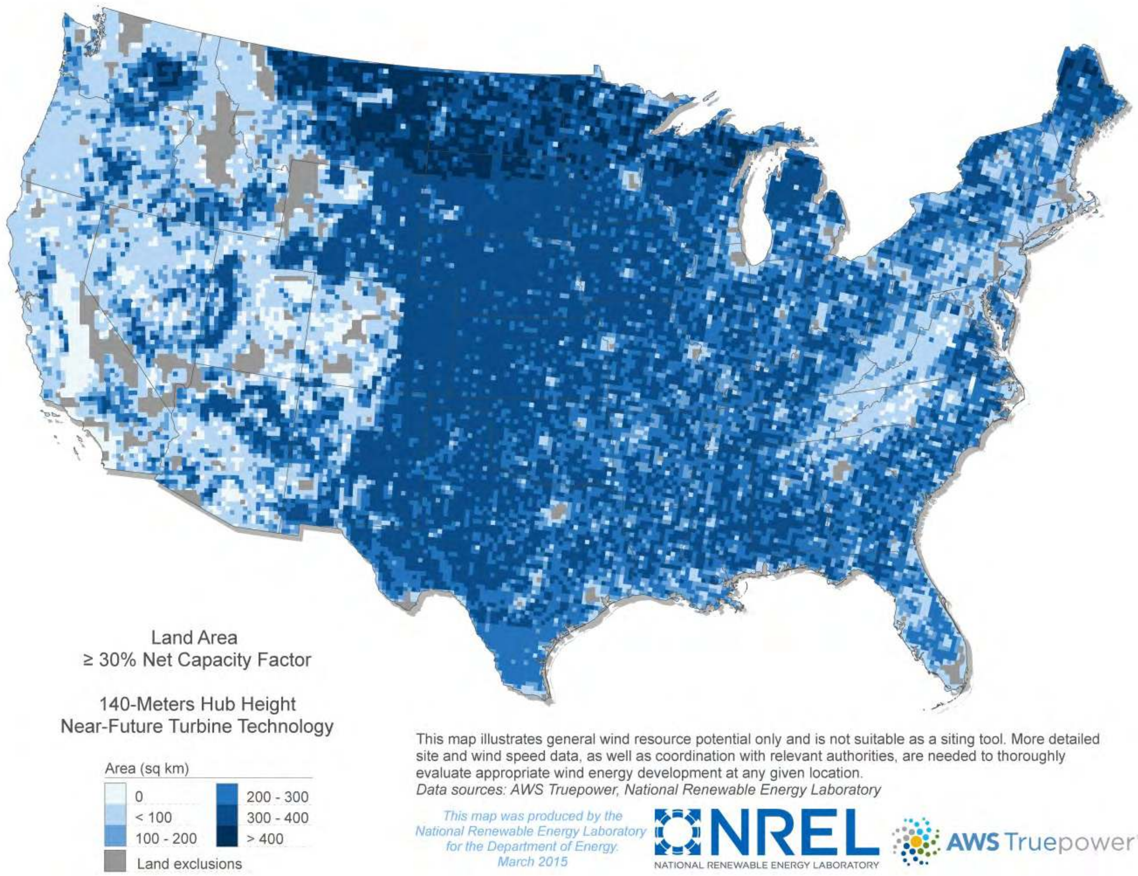


Figure 4-5. Land area achieving a minimum 30% net capacity factor by grid cell, based on lower specific power (150 W/m^2) and a 140-m hub height

Source: DOE 2015

Summary of changes in Technical Potential

Using the historical and future turbine parameters described above and summarized in Table 4-1, technology advancements since 2008 have increased the total land area (as defined by technology potential) that supports a net capacity factor level of 30% or greater by approximately 68% (Table 4-2). Impacts are particularly noteworthy in the West, Midwest, Northeast, and Mid-Atlantic. Continued incremental innovations in rotor size with assumed reductions in specific power, and in hub heights could expand the land area achieving a 30% or greater net capacity factor by an additional 67% (Table 4-2). Impacts would extend into the Southeast, East, Great Lakes, and Interior West.

Table 4-1. Summary of Turbine Parameters Applied in Estimates of Technical Potential

	2008 Turbine Technology (W/m^2)	Current (2013) Turbine Technology (W/m^2)	Near-Future Turbine Technology (W/m^2)
IEC Class 1	400	320	150
IEC Class 2	400	300	150
IEC Class 3	400	210	150

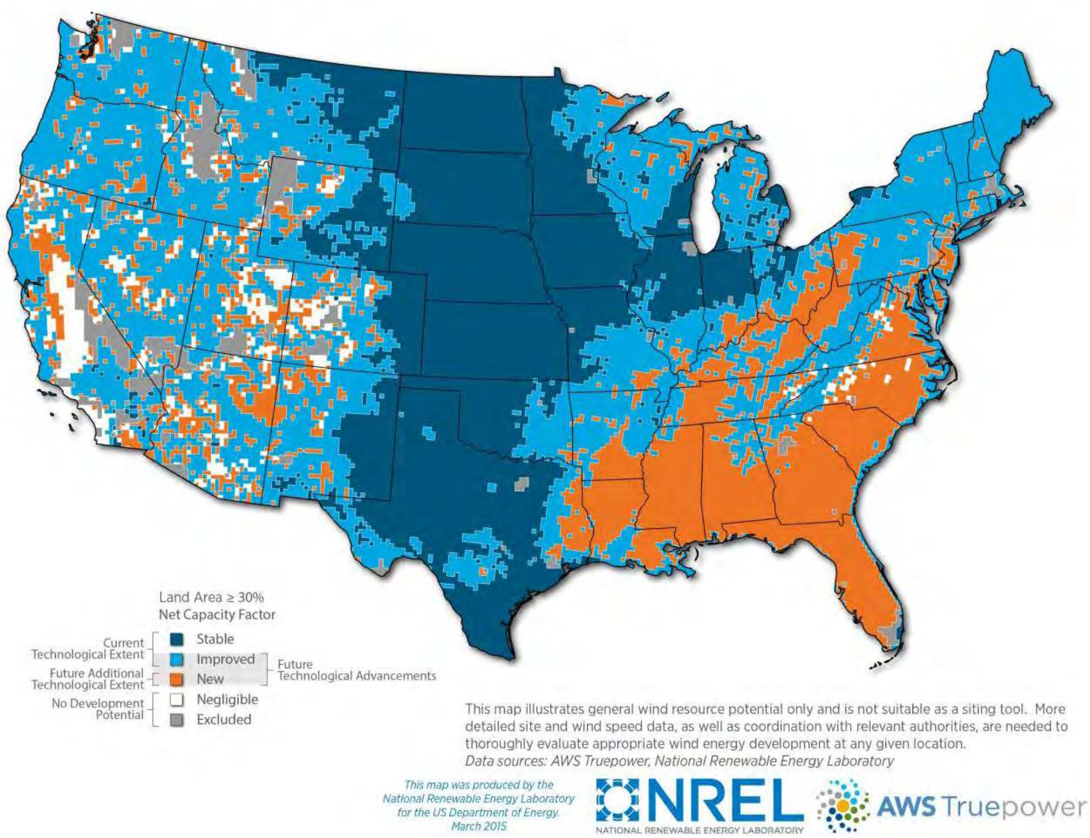
Sources: NREL Database, MAKE Consulting

Table 4–2. Land Area Relative to 2008 Technology

Hub Height	2008 Turbine Technology (km^2)	Current (2013) Turbine Technology (km^2)	% Change from 2008 @ 80 m	Near-Future Turbine Technology (km^2)	% Change from Current (2013) @ 80 m
80m	1,643,000	2,765,000	68%	3,518,000	27%
110m		3,420,000	108%	4,262,000	54%
140m		3,928,000	139%	4,629,000	67%

Sources: NREL Database, MAKE Consulting

More specifically, land area seeing improvements in technical potential extend essentially from the Rocky Mountains to the Pacific Coast and also include portions of the Great Lakes Region, the Ohio River Valley, and the Northeast. Areas with new technical potential include large portions of the Southeast and Appalachia as well as more dispersed areas west of the Rocky Mountains. Figure 4-6 summarizes these results by illustrating the land area with sites that can achieve a 30% net capacity factor based on 2013 technology, the land area with existing potential that could increase with technology improvements, and new land areas achieving the 30% minimum net capacity factor as a function of technology advancement. Based on these data, technological development focused on achieving lower specific power and higher hub heights could affect all but the most wind-rich portions of the country, greatly expanding the technical potential for wind power.



Note: Dark blue coloring identifies high quality wind resource areas that see no change in available land area meeting the 30% minimum net capacity factor threshold with technology advancement because the entire area is capable of achieving this threshold today. Light blue coloring identifies land area that meets the capacity factor threshold today but sees an increase in the proportion of the area able to achieve this threshold as a result of turbine and hub height improvements. Orange coloring identifies new land area able to achieve the minimum 30% net capacity factor level as a result of turbine and hub height improvements.

Figure 4-6. Land area achieving a minimum 30% net capacity factor by grid cell, based on current (2013) and lower specific power (150 W/m^2) and a 140-m hub height

Source: DOE 2015

5.0 Technical Challenges and Opportunities to Accessing Wind at Higher Heights

Since the early 2000s, the industry has been able to significantly lower LCOE by increasing the rotor disk size. The relationship between power, the rotor swept area, and the wind speed discussed in Chapter 3 provides insight into the reasons industry has trended toward taller towers and longer blades (Figure 5-1). And, as discussed in Chapter 4, enabling continuation of these trends through technology innovation holds the promise of opening up entire new U.S. regions to wind deployment.

However, the trends of increasing the swept area and tower heights present their own challenges. Increasing the blade length not only increases the rotor cost because of added material and mass, but also increases the structural loads that the nacelle, rotor, and tower have to withstand. Drivetrains must be able to withstand the greater loads; and the compound effect of heavier structures and increased rotor loads result in the requirement for more substantial foundations. Thus, increases in rotor diameter and hub height are almost always accompanied by increased costs for most components within the wind turbine system. Historic trends indicate that the mass and, therefore, price of a turbine increases as the cube of the rotor diameter increases.

Increased rotor diameter and hub heights also drive higher expenses related to transportation and installation. Larger turbine components require special transportation and support vehicles and can only be transported on certain U.S. highways. The relationship between tower transportation cost and turbine nameplate rating and tower height is depicted in Figure 5-2. The tower mass and cost grow rapidly as a result of the transportation constraint on the base diameter of the tower. Installation of increasingly heavier components on taller towers requires costly special-purpose cranes. While there are still LCOE benefits possible with increases in turbine size and operating height, other constraints such as transportation limitations and lack of crane availability are already limiting technology growth.

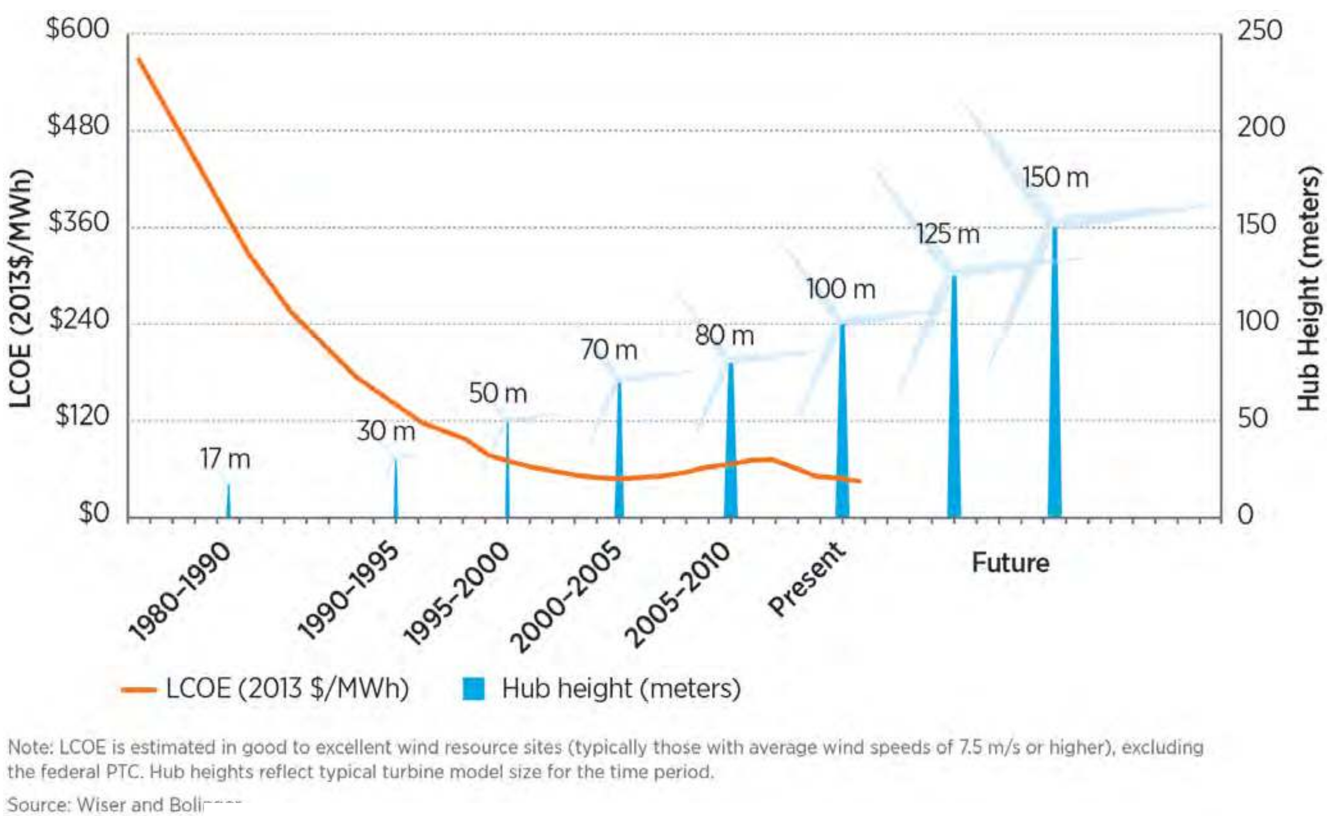


Figure 5-1. Wind technology scale up trends and LCOE
Source: Wiser and Bolinger 2014

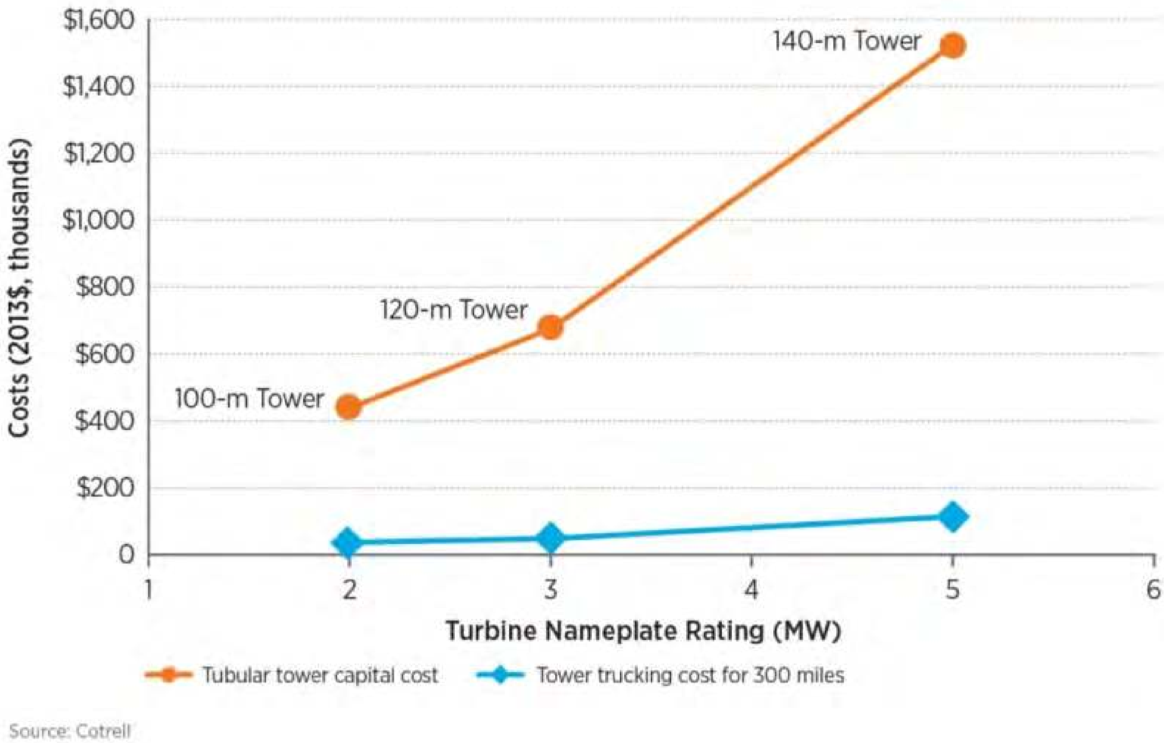


Figure 5-2. Tower transportation cost as a function of turbine nameplate rating and tower height
Source: Cotrell et al. 2014

The U.S. wind market has expanded to include lower wind speed sites (average wind speeds <7.5 meters/second) 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 in higher wind speed resource areas. As a result, from 1998 to 2013, the average estimated quality of the wind resource at 80 m for newly installed wind projects dropped by approximately 10% (Lantz et al. 2014). 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 as manufacturers attempt to balance energy production with transportability. The sections below include discussion of the transportation challenges and potential solutions to those challenges, including how they have been overcome in countries where taller turbines are routinely deployed.

5.1 Technical Challenges

The technical challenges that need to be addressed in order to enable cost-effective wind deployment nationwide can be summarized in three categories: transportation challenges, design optimization and installation challenges, and lower specific power rotor design challenges.

Transportation Logistics

Installed turbine power ratings have continued to rise, reaching an average of 1.87 MW in 2013 including multiple models at 2 MW and higher (Wiser and Bolinger 2014). As original equipment manufacturers (OEMs) seek to capture more wind at lower wind speed sites, average rotor diameters have also increased rapidly. Tower components have similarly increased in size and mass to access better winds higher above the ground. Wind turbine blades longer than 53 m present a transportation obstacle due to the large turning radius, which hinders right of way or encroachment areas within corners or curves on roads and railways (Figures 5-3 and 5-4). 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 permit requirements. 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, the American Wind Energy Association Transportation and Logistics Working Group is coordinating with the American Association of State Highway and

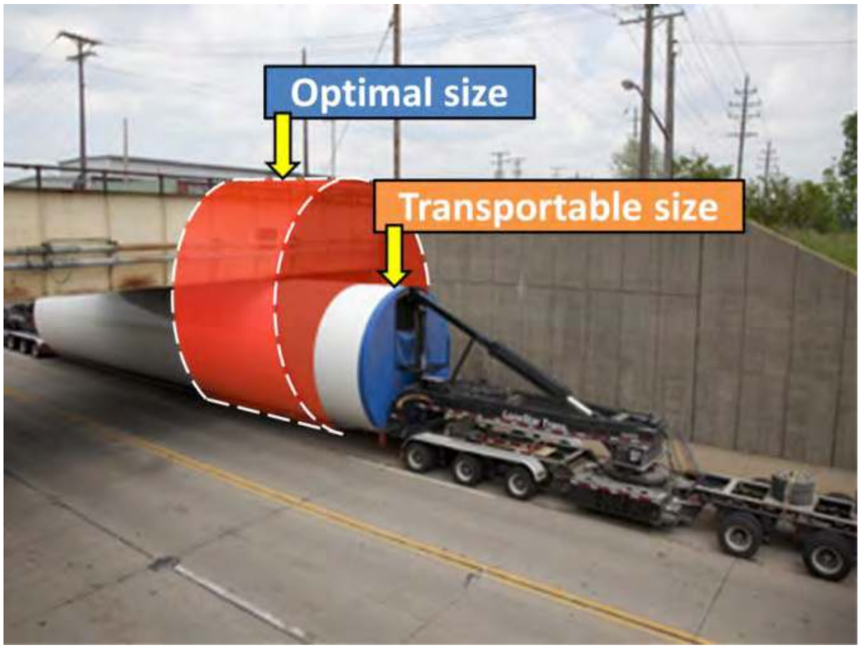


Figure 5-3. Tower diameters are limited by transportation constraints such as bridge height
Source: Keystone Towers

Photo credit: SSP Technology

Figure 5-4. Example of wind turbine blade transportation obstacles

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 (Kubiszewski et al. 2010).

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, such height results in a substantial increase in the mass and cost of rolled steel towers. Under transportation constraints as of 2014, tall towers are not economical in the sizes necessary to deploy wind in low and moderate wind speed land areas that are of interest to the industry and could support cost reductions. These capital costs are substantially higher than the cost to transport the tower sections. Similar transportation/design tradeoffs impact blades with respect to other aspects, such as maximum chord dimensions.

Low Specific Power Rotor Design Impacts

The future technology rotor described in Chapter 4 is 150 W/m^2 compared to current technology of 210 W/m^2. Lower specific power rotors for any given turbine size are physically larger, capturing a greater area of the available wind (Figure 5.5). However, growing the rotor size has system-wide design implications as both aerodynamic and gravity loads increase as the rotor system gets larger unless measures are taken to mitigate those effects. The additional technical challenge for the future technology rotor described here is to increase the rotor size while controlling rotor loads, limiting the impact to other components in the turbine while increasing the capacity factor.

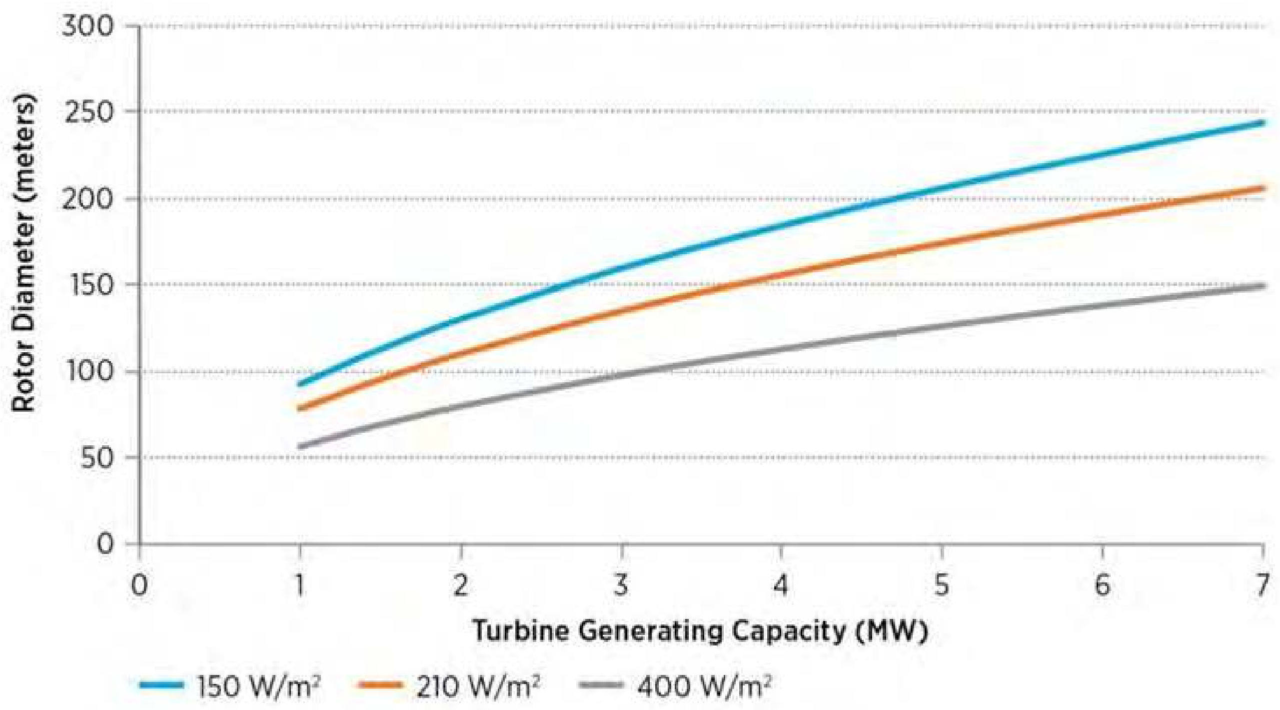


Figure 5-5. Turbine-specific power as a function of turbine generating capacity and rotor diameter

Source: NREL

The design loads for the rotor system consist of ultimate (extreme) loads and fatigue (oscillatory) loads. Many concepts for load reduction exist and have been considered in the past. These concepts fall into two categories, passive and active control. Passive load control is realized through tailoring the structural and material properties of the blades to aero-elastically deform (twist under aerodynamic load) in such a way as to reduce the lift generated from the airfoils. Active control systems work by adjusting the aerodynamic properties of the blades (change of angle of attack or lift coefficient) based on appropriate sensor inputs. This can be accomplished through pitching the entire blade, or through aerodynamic control devices distributed along the blade. Passive control techniques are simpler and reliable, but do not offer as much capability to relieve loads as active devices. Further development of passive and active load alleviation is necessary to progress the technology into commercial products.

5.2 Transportation and Logistics Challenges to Deploying Taller Towers and Larger Rotors in the United States

Technologies that enable larger wind turbines on taller towers create opportunities for further LCOE reductions. However, transportation and logistics challenges limit the size and tower height of land-based turbines that can be deployed in the United States. Addressing these transportation and logistics challenges will allow for deployment of larger state-of-the-art turbines, which may accelerate the development of new markets in low- and moderate-wind-speed regions in the United States and enable LCOE reduction pathways for all land-based wind turbines (Cotrell et al. 2014).

Blade and Tower Transport Challenges

Blade transportation challenges are caused by the difficulty of transporting long, wide blades around turns, through narrow passages, and beneath overhead obstructions on U.S. roads and railways. Although alternate roads can sometimes be used, road weight limits on such "side" roads restrict their accessibility. This challenge generally limits the length of blade that can be transported over roadways to between 53 m and 62 m, depending on the design characteristics of the blade such as the amount of precurve and type of airfoils used.

Transporting the large-diameter tower sections that are the most desirable for tall towers creates a challenge similar to that associated with transporting blades. Tower sections are generally limited to 4.3 m in diameter, or 4.6 m if routes permit, to fit under overhead obstructions (Figure 5-1). Despite this limit, it is possible to transport conventional rolled steel towers sections to reach hub heights up to 160 m by constraining the tower diameter to 4.3 m, increasing the tower wall thickness, and shipping shorter sections that meet the weight limits of U.S. roads. These accommodations, however, result in a rapid increase in the mass and capital cost of rolled steel towers, thus making towers tall enough to access low and moderate speed land areas uneconomic. This increase in capital cost is of greater concern than the cost to transport the tower sections, since the cost of transportation is less than 8% of the combined capital and transportation cost of the towers.

Nacelle Hoisting Challenge

Hoisting the nacelle onto the tower requires the largest crane capacity of all wind turbine components to install because of the lift height and mass. The mass of a 3-MW nacelle is approximately 80 metric tons without the gearbox and generator installed. The availability, scheduling, and logistics of the larger crane classes required to lift progressively larger wind turbine nacelles onto taller towers is increasingly challenging. Crane availability decreases drastically above the 600-ton crane class, thereby making it more difficult to ensure that large cranes will be available for the nacelle lift. Wind turbine OEMs can take measures to reduce the nacelle mass that must be lifted onto the tower. For example, drivetrain components such as the gearbox and generator can be hoisted and installed in the nacelle after the nacelle is installed. However, such methods increase the cost and difficulty of the installation and can only reduce mass by a certain extent Cotrell et al. 2014.

Crane development in the United States is helping to address a shortage of large cranes capable of handling larger wind components. For example, Manitowac Cranes in Wisconsin has developed a new 650-ton crane that is expected to be able to install and service a 3-MW wind turbine nacelle to 140-m hub height and to have a 100-ton capacity at 140 m, compared to the 75-ton capacity of the popular Manitowac 18000 which is being phased out (Manitowoc 2015).

5.3 Global Technology Trends

Tall wind turbines have taken root in Europe since 2008, especially in Germany. More than 45% of wind turbines installed in Europe were 121–150 m tall. In contrast, nearly all turbines installed in the United States in 2013 had hub heights lower than 100 m and towers no taller than 120 m.

The European trend towards taller turbines has stimulated a number of tower construction, crane, and transportation technology developments that can benefit the nation. However, these tower and crane technologies have not been deployed to any great extent in the U.S. market. This is due in part to differences in energy policies, wind resource characteristics, market demand, and transportation infrastructure.

The feed-in tariff system in Germany has incentivized taller towers. This is especially true in the central and southern regions of Germany, which tend to have lower wind resources. The feed-in tariff system in Germany consists of an initial period of high tariff rates, dropping to lower rates over time. Less favorable wind locations receive the high initial tariff for a longer period, effectively incentivizing installations in the central and southern regions. In contrast, the United States has no specific incentives for low wind resource regions.

U.S.-specific wind resource characteristics and market demand also play a role in the generalization of European technology to U.S. applications. In particular, the United States tends to have higher quality wind resource areas and lower population densities, allowing for larger numbers of small turbines to be used to achieve a similar level of operating wind capacity. Where higher quality U.S. wind resources are available, there is also less need to use higher hub heights to access increased wind speeds at higher above-ground levels. Given the significant high quality wind resource available in the United States, wind deployment has been able to expand rapidly without needing to move to regions where it is more costly to access quality wind resources. Market demand and the relative costs of accessing higher quality wind resource sites could change, however, particularly as the existing transmission network to high quality sites is consumed.

The U.S. transportation infrastructure differs significantly from that in Europe. For example, many regions of the United States have access to superior rail freight systems that lend to longer transportation distances. Similarly, with wider highways, over longer distances, the relatively more rural nature of many regions in the United States requires less complex and less expensive hauling equipment than has been developed for many urbanized regions of Europe. But without demand for these solutions for larger components in the United States, the specialized European transportation solutions, driven by European subsidization policies, have not yet been available in the United States.

Despite differences in policy, market demand, wind resource characteristics, and transportation systems, though, many technologies developed in the United States and Europe have potential to be deployed globally. For example, the low transportation costs and substantially lower masses available from steel spiral wound tower technologies in development in the United States are expected to be competitive in Europe as well as growing markets such as Brazil.

5.4 Technology Development

DOE-sponsored wind technology R&D focuses on next-generation component and plant-level innovations. The goal is to accelerate the transfer of such technologies to industry, ultimately reducing LCOE. Industry invests heavily in shorter-term, incremental component-level R&D but has fewer resources dedicated to longer term, next-generation technology development. To bridge this gap, DOE prioritizes high-risk, high-reward R&D and invests in government-sponsored projects to drive innovations. These projects are usually low in terms of technology readiness level (TRL),[16] making them generally beyond the scope of existing industry R&D. DOE focuses on component- and system- prototype development to bring such innovations to mid-TRL status and help transfer innovative, high-potential technology to industry.

Innovative solutions for technologies that will mitigate blade and tower transportation challenges, such as segmented blades and on-site tower manufacturing, are being explored by DOE. Scaling up cost-effective technologies from low TRLs to commercialization, however, will take time and require significant investment in R&D. Continued or expanded national financial support for low-TRL technologies, which are often developed by small and midsize companies, will help bridge the gap to commercialization of these technologies by larger companies with more substantial resources.

In the early 2000s, the DOE Wind Program conducted a comprehensive study of the cost and scaling challenges facing the industry over the coming decade. This study, called the Wind Partnerships for Advanced Component Technology (WindPACT), [17] identified several technical challenges to the continued scaling of land-based wind turbines. The DOE Wind Program used that information to help begin to address those challenges through the Low Wind Speed Technology program. These challenges fall broadly into the categories of towers, blades, and drivetrains. In 2013, the DOE Wind Program undertook a review of wind turbine logistics and planning issues that has resulted in a multi-year phased approach to address the technical challenges slowing the adoption of taller and larger turbines. This will include the designs, materials, and

[16] Low TRL projects focus on applied research and proof of concept.

[17] (Malcolm 2004), (Smith 2001), (WindPACT 2001), (WindPACT 2002)

manufacturing processes to overcome existing fabrication, transportation, and logistics barriers for large blades, taller towers, and larger gearboxes/generators.

Taller Towers

The cost of wind turbine towers 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. 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.

Many alternative tower configurations are in commercial production or being evaluated to overcome transport limitations. These new configurations include on-site fabrication of steel towers, all-concrete towers, hybrid towers that use large diameter concrete bases with conventional tubular steel towers for the upper section, space-frame or lattice structures, and bolted steel shell towers. Many of these concepts are either commercial products, or have been demonstrated at full-scale but are not widely deployed in the United States due to the unfavorable economics. Other technical options include “soft-tower” concepts; standard steel towers with reduced stiffness requirements. The lower tower stiffness reduces the amount of steel required, but necessarily requires the turbine to pass through some of the resonant frequencies of the rotor and tower systems before reaching its nominal operating speed. This approach requires a robust control system that will prevent operation at a resonant frequency which could cause significant structural damage to the turbine.

While there are many possible technical solutions in existence today, the challenge remains to make these solutions cost effective in the United States. Early DOE investments in taller tower technologies have resulted in a commercially available product.

In 2002, a DOE Small Business Innovation Research grant was awarded to Wind Tower Systems, a subsidiary of Wasatch Wind, to develop the space frame tower. Instead of a solid steel tube, this new concept tower consists of a highly optimized design of five custom-shaped legs and interlaced steel struts (Figure 5-6). The space frame tower relies on a metal lattice structure. The structure is essentially a series of connected steel poles and crossbars that create the internal support for the tower, of which component sections can be bolted on top of one another vertically. This metal latticework is then covered with durable sheathing.

Unlike the long, heavy tubular steel sections used to elevate conventional wind turbines, the metal lattice structure of this next-generation tower can be transported by standard flatbed truck and assembled on-site. With this design, space frame towers can support turbines at greater heights, yet weigh and cost less than traditional steel tube towers. In February 2011, General Electric announced its acquisition of the space frame turbine tower technology, and in March 2014, the company’s renewable energy business announced the commercial introduction of its new space frame tower

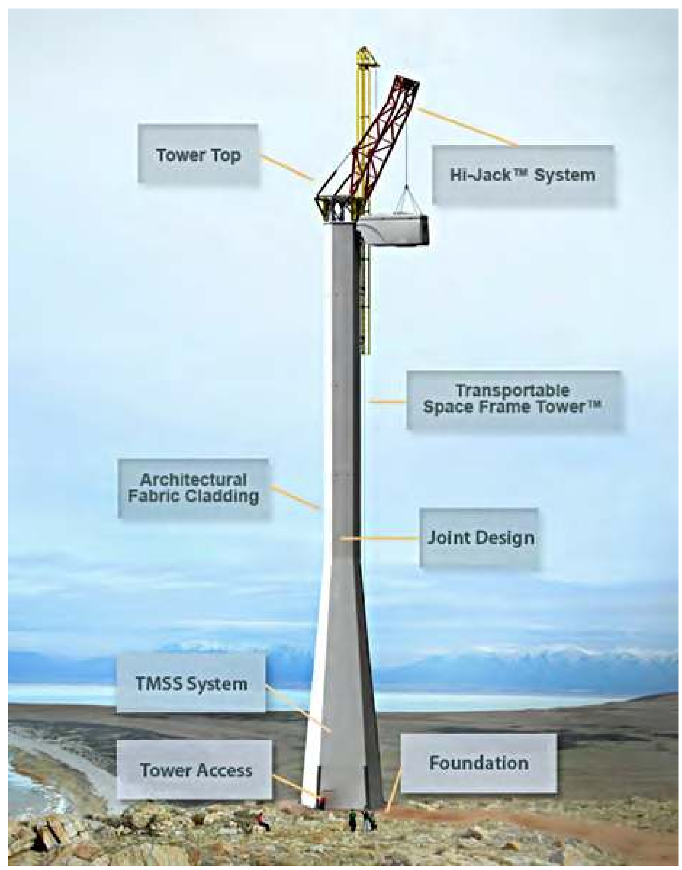


Figure 5-6. Conceptual diagram of the space frame tower system™
Source: GE

for multi-MW wind turbines. General Electric's five-legged enclosed lattice tower enables towers up to 139 m to be built more cost-effectively in previously inaccessible locations, using a logistics-friendly model of standard shipping methods and on-site assembly.

Other tall tower research included awards to Native American Technologies under a National Renewable Energy Laboratory sub-contract, a Small Business Innovation Research grant (2007), and funding from the American Recovery and Reinvestment Act of 2009. This funding was awarded to support Native American Technologies in developing an in-situ fabricated, self-erecting tower; the 150 m UltraTall™.

The UltraTall™ tower is a corrugated tower design concept, originally proposed to the National Renewable Energy Laboratory (NREL) as a design project in the Low Wind Speed Turbine R&D program. The work also included the design of an apparatus to place the nacelle, generator, gear box, rotor, and blades on top of the tower without the use of an external crane. The concept uses an automated thermal forming process to create the corrugated shape for the tower sections. This portable process allows the steel plate to be formed on-site, and the corrugated shape increases the stiffness of the tower and reduces the thickness of the steel by 30%, resulting in cost savings in tower steel and reducing the transportation cost of the steel to the installation site. The UltraTall™ tower concept has not been commercially deployed as of 2014.

Recent DOE Tall Tower Awards

Through competitive solicitations, DOE issued Fiscal Year (FY) 2014 awards to Keystone Tower Systems and Iowa State University for research on taller towers. Keystone Tower Systems is developing an advanced manufacturing technique that enables on-site production of large-diameter, tapered, spiral-welded tubular steel wind turbine towers. On-site production enables towers to surpass the 4.3-m-diameter limit associated with transportation, allowing turbine hub heights to cost effectively increase from 80 m to 140 m and higher. The technology is based on a proven in-field welding process from the pipe industry.

Iowa State University is working to combine high-strength concrete with pre-stressing steel reinforcement to build tower modules comprising easily transportable columns and wall panels. The concept uses hexagonal-shaped columns with post-tensioning and rectangular panels as bracing elements. If successful, the concept will eliminate existing transportation constraints.

Next-Generation Larger Blades

Increasing the capacity factor of a turbine through lower specific power rotors (longer blades) involves tradeoffs between energy capture and turbine structural loads in addition to transportation constraints. Blade technology innovations to achieve a future-technology rotor of 150 W/m^2 will have to address load alleviation through either passive or active aerodynamic controls, advanced materials, and structural designs to reduce blade mass while maintaining adequate stiffness and strength, as well as concepts that can alleviate transportation constraints.

Sophisticated turbine control systems will continue to contribute to increases in energy capture and the reduction of structural loads. Techniques that measure the wind upstream of individual turbines and wind plants, such as LIDAR, provide more accurate information about the flow field and allow control systems to take action before changes in the wind reach the turbines. Important opportunities are available in aerodynamic control to reduce structural loads using independent blade pitch control, as well as aerodynamic devices along the span of the blade.

Wind turbine blades over 53 m in length represent a logistical challenge for transport due to the large turning radius, which hinders right-of-way or encroachment areas within corners or curves. As blades grow longer, the blade chord (airfoil length) also increases to the point where it also becomes a constraint. Future large-diameter root sections of blades may also pose a challenge.

Both industry and government agencies are actively pursuing research to enable larger rotor systems; a few of these efforts are highlighted here.

Through a joint collaboration with DOE's ARPA-E starting in 2013, GE researched fabric-based wind turbine blades targeted at significantly reducing the production costs and mass of the blades. Conventional wind turbines use rigid fiberglass blades that are difficult to manufacture and transport. GE explored the use of tensioned fabric uniquely wrapped around a space frame blade structure, a truss-like, lightweight rigid structure, replacing current clam shell wind blade designs (Figure 5-7). The blade structure was significantly altered, with the intent to allow for easy access and repair to the fabric while maintaining conventional wind turbine performance. A fabric-based blade design could be manufactured in sections and assembled on site, enabling the construction of much larger wind turbines that can capture more wind with significantly lower production and transportation costs.

Through a 2015 Federal Small Business Innovation Research grant, Wetzel Engineering, Inc., proposed R&D to engineer very large wind turbine rotor blades for land-based machines that avoid expensive and logistically challenging transportation requirements. The proposed solution combines two technologies–sectional component-based assembly and in-field assembly–to produce a turbine blade that can be transported in smaller sections and assembled on site (Figure 5-8).

Gamesa has developed a segmented blade design for its G128 4.5-MW wind turbine, leveraging research conducted through participation in UpWind, a European Union-funded research program that explored large-turbine design solutions from 2006 to 2011. The 62.5-m blades (called InnoBlades) feature a bolted joint that can be assembled in the field without compromising the mass and aerodynamic performance compared to conventional blades (Figure 5-9). As of July 2013, twenty seven Innoblade segmented blades have been deployed.[18]

On March 16, 2015, DOE released a Funding Opportunity Announcement (FOA) entitled, "*U.S. Wind Manufacturing: Larger Blades to Access Greater Wind Resources and Lower Costs*."[19] Awards from this FOA will support R&D partnerships aimed at innovative designs and processes for the manufacturing and assembly of wind turbine blades in order to facilitate deployment of the next generation of multi-MW wind turbines. Supported projects will develop cost-competitive integrated solutions that address the challenges of fabricating, transporting over land, and assembling rotor blades longer than 60 m—with design concepts scalable to greater lengths—and installing them at wind turbine hub heights of at least 120 m. The FOA is intended to be forward-looking in addressing U.S. market dynamics and domestic manufacturing opportunities through innovative solutions to constructing and assembling larger blades that can mitigate U.S. transportation constraints.

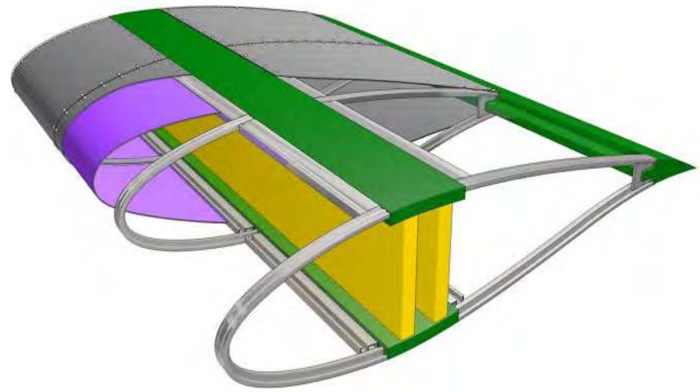


Figure 5-7. Conceptual diagram of a fabric-based wind turbine blade
Photo credit: GE

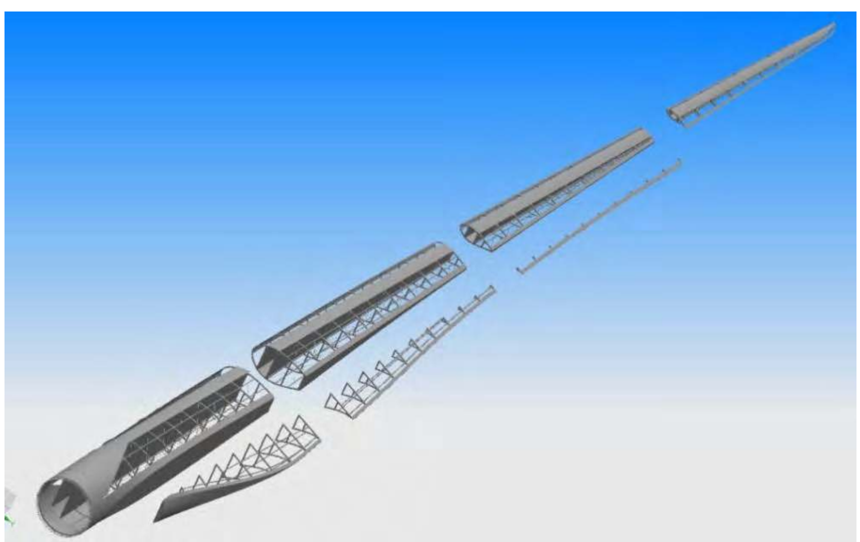


Figure 5-8. Sectional wind turbine rotor blade as proposed by Wetzel Engineering
Photo credit: Wetzel Engineering

[18] http://www.compositesworld.com/articles/modular-design-eases-big-wind-blade-build accessed 05/01/2015

[19] Funding Number: DE-FOA-0001214. http://www1.eere.energy.gov/financing/solicitations_detail.html?sol_id=991

Figure 5-9. Jointed wind turbine rotor blade

Image source: http://www.compositesworld.com/articles/modular-design-eases-big-wind-blade-build. Accessed 5/1/2015

Next-Generation Drivetrains

Continued development is needed to reduce the size, mass, cost and improve reliability and efficiency of the drivetrains and power conversion systems that turn the rotor's rotational power into electrical power. Conventional multi-stage geared approaches, medium-speed systems, and direct-drive architectures each have advantages, and technological development of all three configurations should be continued. High-flux permanent magnets can improve the efficiency of these configurations, and efforts to develop alternatives to the existing rare-earth technologies such as superconducting generators also show great potential. The problems associated with transporting and hoisting heavier drivetrains onto taller towers is expected to become increasingly important as these systems grow in size.

DOE issued a FY 2011 FOA awards to the Advanced Magnet Lab and NREL to support work focused on next-generation drivetrains. Advanced Magnet Lab developed a fully superconducting generator design (rotor and stator). The project was focused on modeling and designing a full system, in addition to testing the cooling system, windings, rotating seals, torque transfer, thermal management, and other components. Advanced Magnet Lab's superconducting winding technology possesses certain advantages that enable the adoption of superconducting generators. A fully superconducting generator offers significant improvements in mass and efficiency compared to conventional permanent magnet generators.

As of FY 2015, an NREL-led team is developing a hybrid design of a single-stage gearbox and medium speed 3.3 kV generator that incorporates new bearing and gear design and advanced silicon carbide power electronics. These advancements target key component-level technological barriers of existing driveline topologies. Phase I is used for design optimization, while Phase II will be used to build and test the prototype. This drivetrain is projected to reduce LCOE through improved reliability, and the design is scalable and can be used to retrofit existing 1.5-MW turbines. Phase II will consist of a full 1.5-MW drivetrain system prototype and testing.

5.5 Future Technology Needs to Address U.S.-Specific Challenges and Opportunities

Further Technology Challenges to Taller Turbines

As with any complex system, changes to individual subsystems have larger, system-wide effects that must be accounted for in the new design. Moving to taller towers and lower specific power rotors will also drive the industry to higher power (larger MW) turbines to take advantage of the economics of scale. Beyond addressing blade, tower and drivetrain logistics, the designer must also consider other aspects that will drive the design of the system. These considerations include advanced aerodynamic controls for blade loads, rotor control systems, bedplates and nacelles and the limitations of the cranes available to install turbines at much higher heights and advanced foundations to handle the larger loads.

Rotor Loads Control

Additional opportunities for innovation in the design of blades include aeroelastic design techniques that shed loads utilizing advanced low-cost, high-strength materials, and active or passive aerodynamic control devices. Recently, turbine designers have adopted passive load alleviation strategies that will allow them to increase the length of the blades without significantly increasing mass. Another alternative is the use of active control strategies to manage and mitigate loads experienced by the turbine within its design envelope. While active load alleviation holds the promise of being more versatile than passive strategies, it is also inherently more risky. Issues such as reliability, fatigue, and maintenance/repair must be addressed before these technologies will be accepted by turbine manufacturers as part of their product offering. Significant research still needs to be performed to mature the active load control concepts and de-risk them adequately before such concepts can be integrated into the next generation of large wind turbine blades. A new generation of active load control strategies that can be economically manufactured and integrated into turbine blades could significantly increase wind deployment at low wind speed sites.

Nacelle Transportation and Hoisting

Over-the-road transportation limitations are based on the length, width, height, and weight of loads, and these limits vary across the United States. Most nacelles and large components are shipped on common 13-axle trailers, which have a load constraint of about 165,000 pounds. As weights move above that threshold, the number of available trailers drops dramatically and the use of dual-lane or line trailers is required. These trailers have diminishing returns in terms of cargo capacity because they are heavier. For example, the capacity of a 19-axle trailer (the largest conventional trailer) is approximately 225,000 pounds (102 tons), which is roughly equivalent to a 4-MW wind turbine nacelle with the drivetrain removed. Innovations to reduce the mass and size of bedplates and nacelles will be necessary to enable taller turbines.

The problems associated with hoisting heavier nacelles onto taller towers are also affecting wind turbine installations and are expected to become increasingly important as these systems grow in scale. A number of potential solutions exist to address these problems. One potential solution is to use more than one crane to hoist the nacelle onto the tower. Dual crane lifts are commonly used in Europe, but are not typically used in the United States. Demonstration projects with dual crane lifts could be used to collect and communicate information about this approach with industry stakeholders.

Foundations

Taller towers coupled with higher capacity wind turbines drive the foundation design. Vertical loads, shear forces and overturning moments are transmitted to the foundation by the tower. It is not possible to simply scale up existing foundation designs; the requirements become unworkable. The logistics of pouring the concrete and coordinating vehicle traffic on site present huge challenges. The result is enormous foundations that are extremely expensive to construct. Development of new foundation designs will be necessary to meet industry cost constraints.

Further Developing Technology

This project identified several transportation and logistics challenges posed by the deployment of land-based wind turbines that continue to grow in size and height, assessed how they affect cost, and provided recommendations for specific actions. The tower-diameter transportation constraint and perceived blade tip height limit are currently the constraints most affecting wind installations today. DOE and industry should continue to seek innovative technical solutions and reduce remaining regulatory uncertainties associated with these issues in the near term.

The challenges and costs associated with transporting taller towers and very long blades with wide chord lengths also affect wind plant deployments and will become more constraining as wind turbines increase in size and height. Similarly, trucking heavy nacelles and blades with larger root diameters could become challenges meriting additional attention. These challenges could be addressed with continued support for the research and development of mitigation technologies.

6.0 Environmental and Human-based Considerations

Like all infrastructure development, wind energy has the potential to cause impacts to the environment, local communities, and other users of space around wind facilities. Knowledge and understanding of wind power's impacts on wildlife such as birds and bats and on communities and human-related uses such as national security and air traffic control radar have improved dramatically through experience and focused research. Careful siting, early and sustained engagement with national security and regulatory agencies as well as local communities, and, where necessary, the deployment of mitigation measures have enabled the wind industry to manage these issues and coexist effectively with its neighbors.

As wind continues to be deployed around the country and the density of wind development increases, sites with limited potential conflicts are likely to become scarce. Despite improvements in understanding impacts and identifying effective mitigation strategies, more work will be required to minimize potential conflicts and maximize the potential for wind's coexistence with its neighbors. This chapter seeks to lay out some of the challenges that may arise as wind energy is deployed in new regions using taller turbines, and proposes for each of these challenges potential solutions that may help to overcome them.

Advanced technologies that will enable taller and larger turbines will not fundamentally change the nature of these challenges to understand the impacts on wildlife, competing uses and public acceptance. Industry and stakeholders must address these existing challenges through responsible siting, engagement and, where appropriate, mitigation. The significant opportunity that these technologies represent will also bring new—and potentially unforeseen—challenges that government, industry, and stakeholders will need to consider These challenges will arise as wind power moves into new areas opened up by technology innovations as well as directly from the height of the turbines themselves.

6.1 Potential Environmental Impacts

Birds

As wind power moves into new areas, more bird species could potentially be affected. For example, the U.S. Fish and Wildlife Service has considered new rules to protect eagles under the Bald and Golden Eagle Protection Act. The wind industry, the environmental community, and the federal government have invested significant resources to address the impacts of wind power on eagles. The focus of these efforts has largely been on impacts on golden eagles, because of past golden eagle mortalities at wind facilities and because wind development has occurred in areas where golden eagles are most common. As wind development begins to move into the Southeast, potential impacts on bald eagles may become more significant—while golden eagles are largely absent from the region, bald eagles are relatively abundant. Moreover, bald and golden eagles are sufficiently different that research aimed at understanding the impacts of wind on golden eagles may provide little insight on wind's potential impacts on bald eagles. Potential interactions may increase with other species of migratory birds as well, since most migrating birds fly higher than the rotor-swept zone of existing turbines (AWWI 2014). Greater rotor heights may increase the potential for interaction between birds and turbines as well as alter the species composition of interactions.

Bats

An existing consideration that may become more difficult to address as turbines increase in size and are deployed in new regions is how to address impacts to bats, which have been shown to be vulnerable to collisions with turbines, particularly during their late summer and early fall migrations. Many bat species have experienced significant population declines from other threats, most notably a fungal disease called White Nose Syndrome. These declines are driving consideration of these species for listing under the Endangered Species Act. Much of the land area opened to development through the use of larger turbines on taller towers is coincident with areas affected by White Nose Syndrome—and, thus, with territory occupied by bat species that could soon be listed under the Endangered Species Act. For example, the U.S. Fish and Wildlife Service issued an interim rule listing the Northern Long-Eared Bat as threatened across its range, which covers states from North Dakota to South Carolina and most of the United States east of the Mississippi River (FWS 2015). Regulatory scrutiny on both new and existing wind projects in these areas is likely to increase as a result.

At the same time, mitigating wind's impacts on bats using existing tools may become more difficult as wind turbines increase in size and move into new areas. Curtailment of wind turbines during the late summer and fall migration—when wind speeds are low and bats are most active—has been shown in most studies to reduce bat mortality at those wind plants by at least 50% (Arnett et al. 2013a). As a result, developers of wind projects proposed in the habitat of sensitive bat species are increasingly asked to implement measures such as permit conditions or voluntary efforts to minimize potential wildlife impacts. Curtailment, however, comes at the cost of the energy and revenue that would have been produced if the turbines were spinning.

At sites with high median wind speeds, curtailment at low wind speeds may be required less often, so the effect of this revenue loss on the economic viability of a project might be relatively minor. In areas where new technology will enable the development of sites with lower wind speeds, such as previously marginal areas in the upper Midwest, Northeast, and Mid-Atlantic, and in entirely new areas such as the Southeast, curtailment of turbines may be required more often during the summer and fall, and the effect on project economics may be greater. Research and development on ultrasonic deterrent devices to keep bats away from turbines has shown promise (Arnett et al. 2013b) and is ongoing. Such technology is immature, however, and further research is needed to increase effectiveness and overcome technical difficulties inherent to ultrasound, as well as to investigate other potential deterrent options.

Surface Footprint

In addition to direct impacts such as turbine strike to birds and bats, surface disturbance associated with wind development can impact wetlands, fish and wildlife habitat, and archeological and paleontological resources. Many of these natural and cultural resources are protected by federal and state law and must be taken into account as part of the federal permitting process. As wind development expands into new regions and uses larger turbines, these surface footprints issues may arise and will need to be accounted for in the siting process.

Potential Mitigation Solutions for Environmental Impacts

Concentrated effort and investment is needed from industry, the federal government, the environmental community and researchers to better understand the potential impacts of wind development on species of concern, habitat, and other natural and cultural resources in newly opened markets such as the Southeast. This understanding will also allow stakeholders to refine existing siting and mitigation measures, and to develop and test new siting and mitigation measures to avoid, minimize, and possibly compensate for the impact of wind energy on these resources.

Bats

In regard to bats, near-term focus and investment is needed to develop mitigation measures that can enable wind and bats to coexist effectively even if bat populations continue to decline for other reasons. These actions would include the following:

1. ***Improve understanding of biological and ecological factors leading to bat mortality at wind facilities.*** Research on bat behavior at wind facilities suggests that bats may be attracted to wind turbines and proposes a number of hypotheses regarding why this may be the case. Little is known, however, about which factors are most important and how they may differ by species and regional or site-specific characteristics (such as whether a facility is in open farmland or on a forested ridgeline, or whether in warmer climates bats may be at risk for longer periods of the year). Systematic testing of these hypotheses through lab and field observation and experimentation for multiple species across a broad range of geographies will be critical to understanding the mechanisms leading to bat mortality, how those mechanisms vary by site and species, and—ultimately—to developing the range of mitigation options that will be needed to address potential impacts.

2. ***Refine existing curtailment measures to maximize mortality reduction while minimizing revenue loss.*** As noted previously, curtailing the operation of wind turbines during low-wind periods in the summer and fall when bats are most active has been shown to reduce bat mortality by 50% or more at several sites. This curtailment, however, comes at a significant cost in lost energy production and revenue (Arnett 2013a) that may be untenable for projects using taller turbines such as those likely to be required in the Southeast. Because mortality varies between nights when curtailment is prescribed, there could be opportunities to better tailor curtailment regimes to reduce lost revenue and increase the economic viability of these options in regions like the Southeast while continuing to reduce bat mortality.

3. ***Expand research on bat deterrent and detection technologies.*** Because of the economic challenges associated with curtailment and other factors that could otherwise render curtailment infeasible or ineffective with particular species or at specific sites, other mitigation options are needed. Initial research has shown promise for ultrasonic deterrent devices (Arnett 2013a). These technologies are limited in maturity, however, and the fact that ultrasound attenuates rapidly as a function of distance makes deterrence across the full rotor-swept zone difficult. DOE's April 2015 announcement (DOE 2015b) of almost $2 million to support the development and demonstration of bat deterrent technologies around wind facilities is a first step to overcome some of

these challenges. More research is needed, however, to bring existing ideas to maturity and develop new deterrent options. This would include basic physiological research to better understand what stimuli (such as UV light) might work best to deter bats. Over the longer term, technologies that can detect the presence of bats and automatically deploy mitigations like deterrents or curtailment would also be useful in improving the effectiveness of mitigation measures and reducing overall cost.

Birds

As of 2015, the U.S. Fish and Wildlife Service was revising its regulations under the Bald and Golden Eagle Protection Act, making compliance rules for wind developers and operators somewhat uncertain. In general terms, dedicated research is needed to understand biological and ecological factors related to interactions between bald eagles and wind turbines. This information can be used to assess the potential magnitude of the issue, improve the ability of regulators and developers to predict risk to bald eagles at particular sites, and begin to consider potential mitigation measures.

Surface Footprint

Understanding the existing natural and culture resources in the project area will continue to be critical in choosing appropriate areas for development and addressing surface footprint issues such as potential impacts on habitat, wetlands, and archeological and paleontological resources. Careful and informed siting can expedite deployment of wind plants. Industry should continue to take advantage of available information on potential resource conflicts (e.g., mapped sage grouse habitat on Bureau of Land Management-administered land) at an early stage of the process and continue to follow best practices in site-specific data collection to ensure the effective protection of affected resources. Numerous tools exist to help facilitate this early screening, such as the Western Association of Fish and Wildlife Agencies' Critical Habitat Assessment Tool (WAFWA 2015), and the Landscape Assessment Tool (AWWI 2013) developed by the American Wind Wildlife Institute and The Nature Conservancy. In areas where data are limited on particular resources of concern, broad-scale collection of baseline data may help facilitate planning. In the absence of such efforts, industry may be required to collect additional site-specific data as part of the project development process.

6.2 Competing Uses

The deployment of larger turbines and expansion into new areas may change how wind power interacts with other uses and missions, such as the regulation of airspace; military training and testing; and national security, air traffic control, and weather radars. The Federal Aviation Administration (FAA) manages the safe and efficient use of the U.S. airspace. Under regulations codified in Title 14 of the Code of Federal Regulations, Part 77, *Safe, Efficient Use, and Preservation of the Navigable Airspace* (14 CFR Part 77), and through the aeronautical study process, the FAA evaluates all proposed structures over 200 feet (60 meters) in height and structures below 200 feet in close proximity to airports for the potential to impact aviation through the physical obstruction of airspace and interference with air traffic control and surveillance radars.

The U.S. Department of Defense (DOD) also evaluates impacts to its missions through the FAA process. The FAA conducts thousands of aeronautical studies for wind turbines every year. Under its regulations, structures over 499 feet (152 meters) above ground level are defined as obstructions to aviation and warrant further study to determine impacts to aviation and the National Airspace System. While the process for evaluating turbines above this height does not differ substantially, further evaluation includes public notice and additional studies. As the wind industry has gradually increased the height of turbines, FAA aeronautical cases for these structures over 500 feet have increased as well.

Wind turbines within the line of sight of radar systems can significantly degrade radar performance and present conflicts with public safety, homeland security, and national defense testing, training, and operation. The increase in land area viable for wind development because of taller towers is likely to increase the number of radar systems impacted by wind turbine radar interference. The increased height of turbines may also increase the impacted distance around each radar system. Increases in height can present obstruction issues for national defense missions, such as low-altitude flight training. The increased height of turbines and the opening of new developable land in regions such as the Southeast may expand the number of areas with impacts to national security and other radar missions, such as the protection of life and property from extreme weather. Additionally, expanding the availability of turbines in new geographies may increase intersections with heavily congested airspace such as the East Coast and Southeast.

The DOD follows a structured process defined in the *Mission Compatibility Evaluation Process (*32 CFR Part 211), in concert with the FAA's obstruction evaluation procedures. The DOD process quantifies impacts and attempts to develop feasible and affordable mitigations for wind developments proposed near military test and training activities, and near national security-related air surveillance and military-unique test radar systems. As turbines get taller, the potential for encroachment on airspace critical to DOD activities such as Military Training Routes and Special Use

Airspace is likely to increase. The Southeast has significant acreage in U.S. military installations and associated training ranges as well as substantial dedicated military airspace, making the siting of wind projects in this region of the United States more challenging with respect to the DOD. The western United States also hosts some of the largest DOD installations and ranges. As such, increased wind power development near critical military test and training ranges in Utah, Nevada, New Mexico, Arizona, and California may become problematic to the DOD.

Potential Mitigation Solutions for Competing Uses

To mitigate potential impacts from wind power on competing uses such as airspace and radar, close coordination across the federal government will be needed to enable agencies with affected missions such as DOD and the Department of Homeland Security to understand and plan for increased potential impacts on their missions in areas with existing wind development. Such coordination will also help agencies anticipate where missions such as air traffic control, military training, and testing activities may be impacted as wind power development moves into new areas. In addition, because taller turbines have the potential to affect radars at greater distances (due to having a longer line of sight), the importance of overcoming radar interference may increase.

In 2012 and 2013, DOE, DOD, FAA, and the Department of Homeland Security conducted a series of flight tests under the Interagency Field Test and Evaluation (IFT&E) program to investigate and address concerns of increasing interference of wind turbines with air surveillance radars. The program had three goals: (1) characterize the impact of wind turbines on existing air surveillance radars; (2) assess near-term mitigation capabilities proposed by industry; and (3) collect data and increase technical understanding of interference issues to advance development of long-term mitigation strategies.

The program consisted of three flight test campaigns spanning 18 months. Each two-week long flight test campaign occurred near a unique type of ground-based air surveillance radar system where a significant number of wind turbines existed in the radar's field of view. Data were collected from federally-owned radar systems, different aircraft types simulating the range of aircraft threats, and a variety of wind-radar mitigation technologies. The program assessed eight different mitigation concepts during the three flight test campaigns.

The IFT&E flight test campaigns yielded substantial outcomes (Karlson et. el. 2014). First, the IFT&E program concluded that regions directly above and very near the wind turbines within line-of-sight of the air surveillance radars experience a significant reduction in the ability to detect aircraft, especially if not operating with a secondary (transponder) system. The tests also documented an increase in the number of false targets generated by the air surveillance radars when the test aircraft flew near large wind turbine projects. These test results suggested a need to consider mitigation technologies, and the IFT&E program documented the promise of several such technologies. These mitigation solutions were not fully mature at the time of testing, however, and the program suggested that additional testing and/or issues be addressed. The data collected in the IFT&E campaigns have been invaluable in R&D efforts to improve modeling and simulation capabilities associated with wind turbine radar interference, as well as in the development of additional mitigation measures such as algorithms to filter turbine interference from radar feeds.

Building from the IFT&E campaigns, DOE, DOD, FAA, and the National Oceanic and Atmospheric Administration signed a Memorandum of Understanding in 2014 to facilitate joint R&D activities to overcome wind turbine–radar interference issues. Activities planned under this Memorandum of Understanding include the development and refinement of modeling and simulation capabilities necessary to adequately assess the impact of wind turbines on critical radar missions; the deployment of near-term, stopgap solutions such as infill or replacement radars that can be deployed to enable wind development in currently constrained areas; and, in the longer term, R&D of mitigation measures such as turbine filtering algorithms. In combination, these activities will make the current fleet of national security and public safety radar systems more resilient to interference from wind turbines, and will ensure the next generation of radar systems incorporates resilience to wind turbine interference as part of the design criteria.

To help the wind industry identify where DOD has critical installations and ranges, Military Training Routes, and special use airspace, the DOD Siting Clearinghouse has made available geospatial files that wind developers can upload into site planning tools (DOD 2015). These tools will become increasingly important as wind plant developers consider locating tall towers near military test and training activities. The DOE Wind Program is also working on additional outreach tools to better inform developers of potential conflicts between wind turbine siting and military missions. These materials can be updated to account for the impact of tall turbines.

6.3 Public Acceptance

Difficulty gaining public acceptance of wind power and creating a solid understanding of it benefits and impacts among both the general public and policy makers may be a challenge to development in areas of the country not experienced with wind. Many areas of the country with installed wind capacity now have 10 or even 20 years of direct experience with the technology. Policy makers in many states and localities have a sophisticated understanding of the benefits and impacts, as well as the ways in which they can address issues through state and local policies. Until DOE published new wind resource maps for taller hub heights in late 2014 (DOE 2014a), which identified areas of the country that could be opened up by advanced turbines on taller towers, there was little understanding that the Southeast might offer any opportunity for wind deployment. The extent of that potential is still not well understood by some stakeholders, including policy makers, utilities, and the general public, which points to a need for neutral, credible information on issues related to wind power in such regions.

Visual impact is an important issue to public acceptance and permitting of wind power development. Siting wind plants to minimize visual impacts to high-value scenic resources is a challenge for land management agencies across the United States. The visibility associated with utility-scale wind plants is dependent on complex interactions of a variety of factors. DOE's Argonne National Laboratory conducted a study for the U.S. Department of the Interior's Bureau of Land Management (Sullivan et al. 2013) that documented 377 observations of five wind plants in Wyoming and Colorado under various lighting and weather conditions. Under favorable viewing conditions, the wind plants were visible to the unaided eye as far out as 36 miles. Within the 36-mile range of visibility, the plants were judged to be major focus of visual attention at up to 12 miles, and likely to be noticed at 23 miles. As the height of wind turbines increase, so will the visibility distance range and their visual dominance within the landscape, which may affect public concern and acceptance of new development using large wind turbines.

Potential Mitigation Solutions for Public Acceptance

To address public acceptance concerns, the wind industry will need to continue best practices in the development of new projects, such as early and frequent engagement with local communities and policy makers at the local and state levels to build trust and generate acceptance. The federal government can provide policy makers, utilities, and other key stakeholders with information about the opportunity wind power may provide in areas such as the Southeast, as well as its potential challenges. This information can facilitate better informed decisions about wind power-related policies as well as about wind power projects directly. For projects that are sited on federal lands, the federal government will also engage in appropriate public involvement for the level of analysis required under the National Environmental Policy Act. Federal agencies must perform an evaluation of environmental impacts pursuant to the National Environmental Policy Act for permitting and leasing wind development on federally-managed lands or for which a federal permit or authorization is required. The level of analysis required under the National Environmental Policy Act will be determined by the appropriate federal agencies and will depend on the type, size, location, and level of risk for the proposed project and its possible environmental effects.

Public acceptance is described by the scientific community in three categories: (1) acceptance of technologies and policies, (2) community acceptance, including acceptance of siting decisions and the permitting process used by the developer and local government, and (3) market acceptance among power consumers and investors. Industry best practices that ensure procedural fairness and access to credible information are critical for public acceptance of wind power at the community level. Neutral intermediaries, such as DOE's Wind Energy Regional Resource Centers, can provide objective information to decision makers and communities about wind power, offering an effective mechanism to foster fair and productive engagement between the industry, other stakeholders, and communities about wind power development.

DOE's Lawrence Berkeley National Laboratory is conducting research that will better define the practices most critical in determining acceptance of existing wind projects. Combined with the existing (albeit limited) body of scientific research on this topic, this research may suggest improvement areas for industry best practices aimed at building community support.

Planning tools that enable industry and relevant land management and regulatory agencies to better predict and avoid visual impacts to natural or cultural resources may increase public acceptance of wind development and reduce cost and risk in the permitting process, particularly on federal lands. To address this, DOE funded Argonne National Laboratory to design, develop, and test a prototype geographic information system (GIS)-based software tool for determining the relative risk of visual impacts from utility-scale wind power development to sensitive visual resources and viewing areas in a given area of interest. The resulting prototype, Visual Impact Risk Assessment and Mitigation Mapping System, or VIRAMMS, is a Web-based GIS server application for creating visual impact risk maps and generating location-specific visual impact mitigation measures and best management practices. The VIRAMMS prototype demonstrated that visual impacts and potential mitigations can be predicted using commonly available data and at an acceptable performance level. Widespread use of such tools could provide land use planners, wind power developers, regulators, and other stakeholders with early area-specific risk assessments of potential visual impacts and means to best mitigate those impacts.

In general, GIS tools that provide the industry, stakeholders, and government agencies a common platform by which to examine potential challenges and benefits associated with wind power can increase the transparency and inclusiveness of the development process and potentially lead to better outcomes. In addition to VIRAMMS and early environmental screening tools such as the Critical Habitat Assessment Tool and Landscape Assessment Tool mentioned previously, more general tools allow for numerous considerations to be overlaid and considered in a single frame. For example, DOE funded NREL to design, develop, and test a prototype GIS-based software tool called Wind Prospector (DOE 2014b) to visualize data and analyze the potential for wind power. Wind Prospector provides data, visualization, querying, and analysis capabilities that allow users to explore many site-specific factors that affect project development potential. Examples include land ownership, proximity of transmission lines, available wind resources, permitting stipulations, and exploration activities (Tegen 2015).

Finally, quantitative analysis of wind technology's benefits and challenges may be useful to increase public understanding and acceptance of wind power in new regions. To be most effective, these analyses should be specific to a spatial area that corresponds to decision making or planning activities. For example, jobs and economic impacts analyses at a regional or state scale are necessary to more accurately reflect assets, priorities, and potential impacts decision makers may consider in evaluating tradeoffs associated with any development. Building from existing studies, additional work is needed to target technical studies at select regions of the country or develop and improve accessible and credible tools that can be used by communities.

7.0 A Pathway Forward

As stated at the outset of this report, the United States has vast wind resources across all 50 states, greater than ten times the 2014 national electricity demand. Potential wind turbine technology innovations–including those that enable higher hub heights, larger rotors, and improved energy capture–provide a real opportunity for significant expansion of U.S. wind power deployment through 2030 and beyond. Such an expansion can provide substantial overall value as an option in the U.S. electricity generation portfolio of domestic, low-carbon, low-pollutant power generation solutions for all 50 states.

The Opportunity

DOE's *Wind Vision* report (DOE 2015) found that through continued innovation in technology and markets, such expansion of wind deployment to provide 10% of electricity consumption by 2020 and 20% of electricity consumption by 2030 is both feasible and economically compelling. As discussed in Chapter 1, the *Wind Vision* report found significant reductions in GHG emissions, air pollution emissions, and water use savings through 2030 and beyond due to increased wind deployments. Chapter 4 of this report demonstrated that deployment of advanced turbines at hub heights of 110 m and 140 m (and assuming a specific power of 150 W/m^2 and net capacity factor of 30%) increases the technical potential for U.S. wind deployment to an area of 4.3 km^2 and 4.6 million km^2, respectively, up from 2.8 million km^2 in 2013 at a 80-m hub height. This expanded technical potential is primarily in the Southeast United States, with improved deployment potential for wind in the Northeast and throughout the West as well.

The Challenge

As discussed in this report, realizing the national benefits of expanding wind deployment into new regions such as the Southeastern United States can be facilitated by technology innovation, transportation and logistical solutions, and cost reductions. It will also require developing a detailed understanding of the wind resource as well as responsibly addressing environmental and human use considerations. Participation by a wide range of stakeholders is needed to shape the pathway forward, and to engage in concerted and coordinated actions to realize the potential of U.S. wind power.

Leveraging the Wind Vision Roadmap

The *Wind Vision* report (DOE 2015) provided a broad-reaching roadmap aimed at reducing wind costs, expanding developable areas, and increasing economic value for the nation. The core *Wind Vision Roadmap* actions fall into nine action areas: wind power resources and site characterization; wind plant technology advancement; supply chain, manufacturing, and logistics; wind power performance, reliability, and safety; wind electricity delivery and integration; wind siting and permitting; collaboration, education, and outreach; workforce development; and policy analysis. Chapters 5 and 6 of this report complement the *Wind Vision Roadmap* activities, and further refine specific activities to accomplish geographic expansion to all 50 states through taller towers, larger rotors, and increased energy capture. Just as the *Wind Vision Roadmap* is not prescriptive, this report does not detail how suggested actions are to be accomplished. It is left to the responsible organizations to determine the optimum timing and sequences of specific activities.

7.1 Addressing Wind Turbine Technology Challenges

Optimizing the cost of energy from wind plants to support expanded deployment requires the simultaneous treatment of many variables as a system, from individual components to the wind plant as a whole, and even wind plant interaction with the transmission grid and electricity markets. In addition to addressing the logistical and transport constraints of larger blades, towers, and drivetrains, wind system design considerations are needed including advanced aerodynamic controls for blade loads; rotor control systems, next-generation bedplates and nacelles; innovations to overcome the limitations of the cranes available for installation of turbines at higher hub heights; and advanced foundations to handle the larger loads.

Towers

The cost of wind turbine towers increases rapidly with increasing height, creating a trade-off between tower cost and the value of added energy production. Many taller tower concepts are either commercial products or have been demonstrated at full-scale, but are not yet widely deployed in the United States due to unfavorable economics. Development of advanced manufacturing techniques for taller towers, such as enabling modular assembly or on-site tower production, represents a significant opportunity for the wind industry and its supply chain.

Rotors

Increasing the capacity factor of a wind turbine through lower-specific-power rotors (longer blades) involves tradeoffs between energy capture and turbine structural loads in addition to transportation constraints. Continued development of sophisticated turbine control systems, including those that take into account interactions between turbines within a wind plant, as well as real-time wind flow field measurements, can contribute to increased energy capture and reduced structural loads. Opportunities for innovation in the design of blades include aeroelastic design techniques that shed loads utilizing advanced low-cost, high-strength materials, and active or passive aerodynamic control devices.

Drivetrains

Continued development is needed to reduce the size, mass, and cost, and to improve the reliability and efficiency of wind turbine drivetrains and power conversion systems. Opportunities exist for continued improvement of conventional multi-stage geared approaches, medium-speed systems, and direct-drive architectures. High-flux permanent magnets can potentially improve the efficiency of these configurations, and efforts to develop alternatives to the existing rare-earth technologies such as superconducting generators also show great potential.

Transportation and Logistics

Transporting long, wide wind turbine blades is difficult due to turns, narrow passages, and overhead obstructions on U.S. roads and railways, with the length of blade that can be transported over roadways generally limited to between 53 m and 62 m. Transportation of large-diameter tower sections encounters similar difficulties, with diameters limited to 4.3 m to 4.6 m, far below the optimum diameter for the taller towers discussed in this report. Tower concepts such as sectional-component-based assembly and in-field assembly, can reduce the transportation challenges for wind turbine rotor blades as well. Hoisting wind turbine nacelles onto taller towers requires the largest crane capacity of all wind turbine components to install due to the lift height onto the tower and mass of the nacelle, and issues associated with transporting and hoisting heavier drivetrains onto taller towers is expected to become increasingly important as these systems grow in size. Dual crane lifts, commonly used in Europe, present one opportunity among many to address this issue.

7.2 Addressing Environmental and Human Use Considerations

Successful expansion of wind deployment into new regions of the United States requires much more than technical innovation alone. Topics for action include addressing consideration of birds, bats, land-use footprint, competing uses, and public acceptance.

Birds

More bird species could potentially be affected as wind moves into new areas, and increasing rotor heights may increase the potential for interaction between birds and turbines. One issue in particular is the difference in interactions between Golden Eagles and wind turbines, of which there is significant experience–and the interaction of Bald Eagles with wind turbines, of which there is little or no experience. Dedicated research is needed to understand the biological and ecological factors related to potential interactions between Bald Eagles and wind, improve the ability of regulators and developers to predict risk to Bald Eagles at particular sites, and assess potential mitigation measures.

Bats

Because bats are vulnerable to collisions with wind turbines–particularly during times of migration–as well as to diseases such as White Nose Syndrome, mitigating wind's impacts on bats using existing tools may become more difficult as wind turbines get larger and move into new areas. Near-term focus and investment are needed to develop mitigation measures that can enable wind and bats to coexist effectively even if bat populations continue to decline because of other sources of mortality. These actions would include improving understanding of biological and ecological factors leading to bat mortality at wind facilities; refining curtailment measures currently in use to minimize mortality and revenue loss; and expanded research on bat deterrent and detection technologies.

Surface Footprint

Surface disturbance associated with wind development has the potential to impact wetlands, fish and wildlife habitat, and archeological and paleontological resources. Understanding these potential impacts and using tools for early site screening can support careful and informed siting of wind facilities. In areas where data are limited on particular resources of concern, additional collection of baseline data at a broad scale may help to facilitate planning.

Competing Uses

The deployment of larger turbines and expansion into new areas may change the landscape of how wind energy interacts with other uses and missions, such as the regulation of airspace; military training and testing; and national security, air traffic control and weather radars. Close coordination across the federal government will be needed to enable agencies with effected missions to understand and plan for increased potential impacts on their missions in areas with existing wind development, as well as to anticipate where missions may be impacted as wind development moves into new areas. Development and refinement of modeling and simulation capabilities are needed to adequately assess the impact of wind turbines on critical radar missions; the deployment of near-term solutions such as infill or replacement; and continued research and development of mitigation measures such as turbine-filtering algorithms.

Public Acceptance

Because the extent of wind energy potential in new geographic areas such as the Southeastern United States is not well-understood by a wide range of stakeholders, including policymakers, utilities, and the general public, the creation and dissemination of neutral, credible information on issues related to wind energy in such regions is needed. Industry best practices that ensure procedural fairness and access to credible information are critical for public acceptance of wind technologies at the community level. Continued development of GIS tools that provide the industry, stakeholders, and agencies a common platform to look at the potential challenges and benefits associated with wind energy development can increase the transparency and inclusiveness of the development process and potentially lead to better outcomes. Finally, quantitative analysis of wind technology's benefits and challenges may also be useful in increasing public understanding and acceptance of wind energy technologies in new regions.

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