US Wind Energy by 2030

Florida Board of Professional Engineers
Approved Course No. 0010329

4 PDH Hours

A test is provided to assess your comprehension of the course material – 24 questions have been chosen from each of the above sections. You will need to answer at least 17 out of 24 questions correctly (>70%) in order to pass the overall course. You can review the course material and re-take the test if needed.

You are required to review each section of the course in its entirety. Because this course information is part of your Professional Licensure requirements it is important that your knowledge of the course contents and your ability to pass the test is based on your individual efforts.

Course Description:

This material is based entirely on the information published by the U.S. Department of Energy (DOE) on a scenario of 20% contribution of Wind Power to meet the US Electricity needs by 2030. The course considers the impacts of a modeled energy scenario in which wind provides 20% of U.S. electricity by 2030 – the issues, costs, and potential outcomes. Specific areas of consideration include: (1) a review of turbine technologies, (2) transmission and integration, (3) energy markets, (4) Manufacturing, jobs, and materials, and (5) siting and environmental effects.

How to reach Us …

If you have any questions regarding this course or any of the content contained herein you are encouraged to contact us at Easy-PDH.com. Our normal business hours are Monday through Friday, 10:00 AM to 4:00 PM; any inquiries will be answered within 2 days or less. Contact us by:

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US Wind Energy by 2030

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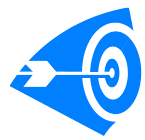
 Search for Test Questions and the relevant review section	 Q1 Search the PDF for: Q1 for Question 1, Q2 for Question 2, Q3 for Question 3, Etc… (Look for the icon on the left to keep you ON Target!)

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24 QUESTIONS

Q1: This course considers the effects of how much wind energy being provided to meet the US electricity needs by 2030:

(A) 15 percent
(B) 20 percent
(C) 25 percent
(D) 30 percent

Q2: In 2006, the cumulative installed capacity of Wind Capacity in the US was approaching:

(A) 12,000 MW
(B) 9,000 MW
(C) 6,000 MW
(D) 3,000 MW

Q3: Wind Energy got its start in what US State in the 1970s:

(A) North Dakota
(B) South Dakota
(C) California
(D) Utah

Q4: All of the following states are expected to have NO Wind development by 2030 EXCEPT:

(A) Alabama
(B) Louisiana
(C) Mississippi
(D) Georgia

Q5: The 20% Wind Scenario presented offers potentially positive impacts including:

(A) greenhouse gas reductions
(B) water conservation
(C) energy security
(D) All of the Above

Q6: With Wind, potential reductions in water consumption in the US Electric sector could approach:

(A) 4 quadrillion gallons
(B) 4 trillion gallons
(C) 40 billion gallons
(D) 400 million gallons

Q7: The wind energy evolution can be compared to the history of the automotive industry in the United States where in what year was the first Model T production run:

(A) 1908
(B) 1910
(C) 1912
(D) 1914

Q8: Modern wind turbines are installed in arrays of how many machines:

(A) 30 to 120 mchines
(B) 30 to 150 machines
(C) 30 to 180 machines
(D) 30 to 210 machines

Q9: In the 1990s the largest wind turbine size was:

(A) 100 kW
(B) 300 kW
(C) 500 kW
(D) 750 kW

Q10: Named after a well-known wind turbine pioneer, The maximum amount of energy that can be extracted from a fluid stream by a device with the same working area as the stream cross section is called:

(A) the Betz Limit
(B) the Belz limit
(C) the Bezt Limit
(D) the Bezz Limit

Q11: The drive train of a Wind Turbine consists of:

(A) gearbox
(B) generator
(C) power converter
(D) All of the Above

Q12: What can be used to reduce tower-top motion, power fluctuations, asymmetric rotor loads, and even individual blade loads:

(A) Active controls using independent blade pitch
(B) control of generator torque
(C) tower height
(D) A and B

Q13: **Taller towers are being designed for what height in order to increase capacity factors:**

(A) 120 feet
(B) 120 meters
(C) 150 feet
(D) 150 meters

Q14: **With a plant age approaching 20 years, what is the highest and most likely repair:**

(A) controls and sensors
(B) motors and switchgear
(C) structural
(D) pitch drive

Q15: **Of the contiguous 48 states, how many have a coastal boundary which could be used for an offshore wind installation:**

(A) 24
(B) 26
(C) 28
(D) 30

Q16: **Distributed wind technology (DWT) applications refer to what type of installation:**

(A) turbine installations on the transmission side of the utility meter
(B) turbine installations on the customer side of the utility meter
(C) turbine installations on the distribution side of the utility meter
(D) turbine installations on the remote side of the utility meter

Q17: **Small Turbine wind systems are typically what size:**

(A) 100 kW or less
(B) 200 kW or less
(C) 500 kW or less
(D) 1000 kW or less

Q18: **Advanced Blade manufacturing advancements in the development of Distributed wind technology (DWT) applications include:**

(A) injection molding techniques
(B) compression molding techniques
(C) reaction injection molding techniques
(D) All of the Above

Q19: **Between 2001 and 2006, the wind industry in the United States has grown by an average of WHAT annually:**

(A) 17 percent
(B) 22 percent
(C) 27 percent
(D) 44 percent

Q20: **The use of carbon fiber in turbine blades in 2030 alone would increase demand by nearly:**

(A) double
(B) triple
(C) quadruple
(D) five times

Q21: **NREL is an acronym for:**

(A) Nuclear Reliability Electrical Listing
(B) National Reliability Electrical Listing
(C) National Renewable Energy Laboratory
(D) National Renewable Electrical Laboratory

Q22: **The largest concentration of U.S. wind turbine component manufacturers is located in what region:**

(A) Midwest
(B) Northeast
(C) South
(D) West

Q23: **The Minnesota West Community and Technical College has a Wind technology-related educational program that is located in what City and State:**

(A) Canby Maine
(B) Minneapolis, Minnesota
(C) Saint Paul, Minnesota
(D) Duluth, Minnesota

Q24: **Key materials are crucial to the manufacturing of wind turbines. How much fiberglass is used in the construction of a wind turbine:**

(A) 9 metric tons
(B) 90 metric tons
(C) 9 metric tons per kW of turbine capacity
(D) 9 metric tons per MW of turbine capacity

END OF TEST QUESTIONS

U.S. Department of Energy

Energy Efficiency and Renewable Energy

Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

20% Wind Energy by 2030

Increasing Wind Energy's Contribution to U.S. Electricity Supply

July 2008

Chapter 1. Executive Summary & Overview

1.1 INTRODUCTION AND COLLABORATIVE APPROACH

Q1

Energy prices, supply uncertainties, and environmental concerns are driving the United States to rethink its energy mix and develop diverse sources of clean, renewable energy. The nation is working toward generating more energy from domestic resources—energy that can be cost-effective and replaced or "renewed" without contributing to climate change or major adverse environmental impacts.

In 2006, President Bush emphasized the nation's need for greater energy efficiency and a more diversified energy portfolio. This led to a collaborative effort to explore a modeled energy scenario in which wind provides 20% of U.S. electricity by 2030. Members of this 20% Wind collaborative (see 20% Wind Scenario sidebar) produced this report to start the discussion about issues, costs, and potential outcomes associated with the 20% Wind Scenario. A 20% Wind Scenario in 2030, while ambitious, could be feasible if the significant challenges identified in this report are overcome.

This report was prepared by DOE in a joint effort with industry, government, and the nation's national laboratories (primarily the National Renewable Energy Laboratory and Lawrence Berkeley National Laboratory). The report considers some associated challenges, estimates the impacts, and discusses specific needs and outcomes in the areas of technology, manufacturing and employment, transmission and grid integration, markets, siting strategies, and potential environmental effects associated with a 20% Wind Scenario.

20% Wind Scenario: Wind Energy Provides 20% of U.S. Electricity Needs by 2030

Key Issues to Examine:

- Does the nation have sufficient wind energy resources?
- What are the wind technology requirements?
- Does sufficient manufacturing capability exist?
- What are some of the key impacts?
- Can the electric network accommodate 20% wind?
- What are the environmental impacts?
- Is the scenario feasible?

Assessment Participants:

- U.S. Department of Energy (DOE)
  - Office of Energy Efficiency and Renewable Energy (EERE), Office of Electricity Delivery and Energy Reliability (OE), and Power Marketing Administrations (PMAs)
  - National Renewable Energy Laboratory (NREL)
  - Lawrence Berkeley National Laboratory (Berkeley Lab)
  - Sandia National Laboratories (SNL)
- Black & Veatch engineering and consulting firm
- American Wind Energy Association (AWEA)
  - Leading wind manufacturers and suppliers
  - Developers and electric utilities
  - Others in the wind industry

In its Annual Energy Outlook 2007, the U.S. Energy Information Administration (EIA) estimates that U.S. electricity demand will grow by 39% from 2005 to 2030, reaching 5.8 billion megawatt-hours (MWh) by 2030. To meet 20% of that demand, U.S. wind power capacity would have to reach more than 300 gigawatts (GW) or more than 300,000 megawatts (MW). This growth represents an increase of more than 290 GW within 23 years.[1]

The data analysis and model runs for this report were concluded in mid-2007. All data and information in the report are based on wind data available through the end of 2006. At that time, the U.S. wind power fleet numbered 11.6 GW and spanned 34 states. In 2007, 5,244 MW of new wind generation were installed.[2] With these additions, American wind plants are expected to generate an estimated 48 billion kilowatt-hours (kWh) of wind energy in 2008, more than 1% of U.S. electricity supply. This capacity addition of 5,244 MW in 2007 exceeds the more conservative growth trajectory developed for the 20% Wind Scenario of about 4,000 MW/year in 2007 and 2008. The wind industry is on track to grow to a size capable of installing 16,000 MW/year, consistent with the latter years in the 20% Wind Scenario, more quickly than the trajectory used for this analysis.

1.1.1 Scope

This report examines some of the costs, challenges, and key impacts of generating 20% of the nation's electricity from wind energy in 2030. Specifically, it investigates requirements and outcomes in the areas of technology, manufacturing, transmission and integration, markets, environment, and siting.

The modeling done for this report estimates that wind power installations with capacities of more than 300 gigawatts (GW) would be needed for the 20% Wind Scenario. Increasing U.S. wind power to this level from 11.6 GW in 2006 would require significant changes in transmission, manufacturing, and markets. This report presents an analysis of one specific scenario for reaching the 20% level and contrasts it to a scenario of no wind growth beyond the level reached in 2006. Major assumptions in the analysis have been highlighted throughout the document and have been summarized in the appendices. These assumptions may be considered optimistic. In this report, no sensitivity analyses have been done to estimate the impact that changes in the assumptions would have on the information presented here. As summarized at the end of this chapter, the analysis provides an overview of some potential impacts of these two scenarios by 2030. This report does not compare the Wind Scenario to other energy portfolio options, nor does it outline an action plan.

To successfully address energy security and environmental issues, the nation needs to pursue a portfolio of energy options. None of these options by itself can fully address these issues; there is no "silver bullet." This technical report examines one potential scenario in which wind power serves as a significant element in the portfolio. However, the 20% Wind Scenario is not a prediction of the future. Instead, it paints a picture of what a particular 20% Wind Scenario could mean for the nation.

[1] AEO data from 2007 were used in this report. AEO released new data in March of 2008, which were not incorporated into this report. While the new EIA data could change specific numbers in the report, it would not change the overall message of the report.

[2] According to AWEA's 2007 Market Report of January 2008, the U.S. wind energy industry installed 5,244 MW in 2007, expanding the nation's total wind power generating capacity by 45% in a single calendar year and more than doubling the 2006 installation of 2,454 MW. Government sources for validation of 2007 installations were not available at the time this report was written.

1.1.2 Contributors

Report contributors include a broad cross section of key stakeholders, including leaders from the nation's utility sector, environmental communities, wildlife advocacy groups, energy industries, the government and policy sectors, investors, and public and private businesses. In all, the report reflects input from more than 50 key energy stakeholder organizations and corporations. Appendix D contains a list of contributors. Research and modeling was conducted by experts within the electric industry, government, and other organizations.

This report is not an authoritative expression of policy perspectives or opinions held by representatives of DOE.

1.1.3 Assumptions and Process

To establish the groundwork for this report, the engineering company Black & Veatch (Overland Park, Kansas) analyzed the market potential for significant wind energy growth, quantified the potential U.S. wind supply, and developed cost supply curves for the wind resource. In consultation with DOE, NREL, AWEA, and wind industry partners, future wind energy cost and performance projections were developed. Similar projections for conventional generation technologies were developed based on Black & Veatch experience with power plant design and construction (Black & Veatch 2007).

To identify a range of challenges, possible solutions, and key impacts of providing 20% of the nation's electricity from wind, the stakeholders in the 20% Wind Scenario effort convened expert task forces to examine specific areas

Wind Energy Deployment System Model Assumptions (See Appendices A and B)

- The assumptions used for the WinDS model were obtained from a number of sources, including technical experts (see Appendix D), the WinDS base case (Denholm and Short 2006), AEO 2007 (EIA 2007), and a study performed by Black & Veatch (2007). These assumptions include projections of future costs and performance for all generation technologies, transmission system expansion costs, wind resources as a function of geographic location within the continental United States, and projected growth rates for wind generation.
- Wind energy generation is prescribed annually on a national level in order to reach 20% wind energy by 2030:
  - A stable policy environment supports accelerated wind deployment.
  - Balance of generation is economically optimized with no policy changes from those in place today (e.g., no production tax credit [PTC] beyond 12/31/08).
  - Technology cost and performance assumptions as well as electric grid expansion and operation assumptions that affect the direct electric system cost.
- Land-based and offshore wind energy technology cost reductions and performance improvements are expected by 2030 (see tables A-1, B-10, and B-11). Assumes that capital costs would be reduced by 10% over the next two decades and capacity factors would be increased by about 15% (corresponding to a 15% increase in annual energy generation by a wind plant)
- Future environmental study and permit requirements do not add significant costs to wind technology.
- Fossil fuel technology costs and performance are generally flat between 2005 and 2030 (see tables A-1 and B-13).
- Nuclear technology cost reductions are expected by 2030 (see tables A-1 and B-13).
- Reserve and capacity margins are calculated at the North American Electric Reliability Corporation (NERC) region level, and new transmission capacity is added as needed (see sections A.2.2 and B.3).
- Wind resource as a function of geographic location from various sources (see Table B-8).
- Projected electricity demand, financing assumptions, and fuel prices are based on *Annual Energy Outlook* (EIA 2007; see sections B.1, B.2, and B.4.2).
- Cost of new transmission is generally split between the originating project, be it wind or conventional generation, and the ratepayers within the region.
- Ten percent of existing grid capacity is available for wind energy.
- Existing long-term power purchase agreements are not implemented in WinDS. The model assumes that local load is met by the generation technologies in a given region.
- Assumes that the contributions to U.S. electricity supplies from other renewable sources of energy would remain at 2006 levels in both scenarios.

critical to this endeavor: Technology and Applications, Manufacturing and Materials, Environmental and Siting Impacts, Electricity Markets, Transmission and Integration, and Supporting Analysis. These teams conducted in-depth analyses of potential impacts, using related studies and various analytic tools to examine the benefits and costs. (See Appendix D for the task force participants.)

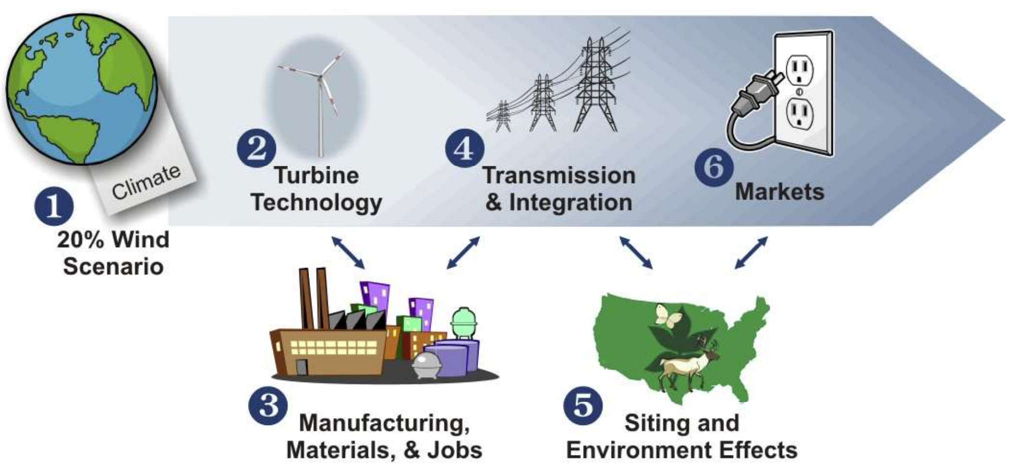
NREL's Wind Deployment System (WinDS) model[3] was employed to create a scenario that paints a "picture" of this level of wind energy generation and evaluates some impacts associated with wind. Assumptions about the future of the U.S. electric generation and transmission sector were developed in consultation with the task forces and other parties. Some assumptions in this analysis could be considered optimistic. Examples of assumptions used in this analysis are listed in the "Wind Energy Deployment System Model Assumptions" text box and are presented in detail in Appendices A and B. For comparison, the modeling team contrasted the 20% Wind Scenario impacts to a reference case characterized by no growth in U.S. wind capacity or other renewable energy sources after 2006.

In the course of the 20% Wind Scenario process, two workshops were held to define and refine the work plan, present and discuss preliminary results, and obtain relevant input from key stakeholders external to the report preparation effort.

1.1.4 Report Structure

The 20% Wind Scenario in 2030 would require improved turbine technology to generate wind power, significant changes in transmission systems to deliver it through the electric grid, and large expanded markets to purchase and use it. In turn, these essential changes in the power generation and delivery process would involve supporting changes and capabilities in manufacturing, policy development, and environmental regulation. As shown in Figure 1-1, the chapters of this report address some of the requirements and impacts in each of these areas. Detailed discussions of the modeling process, assumptions, and results can be found in Appendices A through C.

Figure 1-1. Report chapters

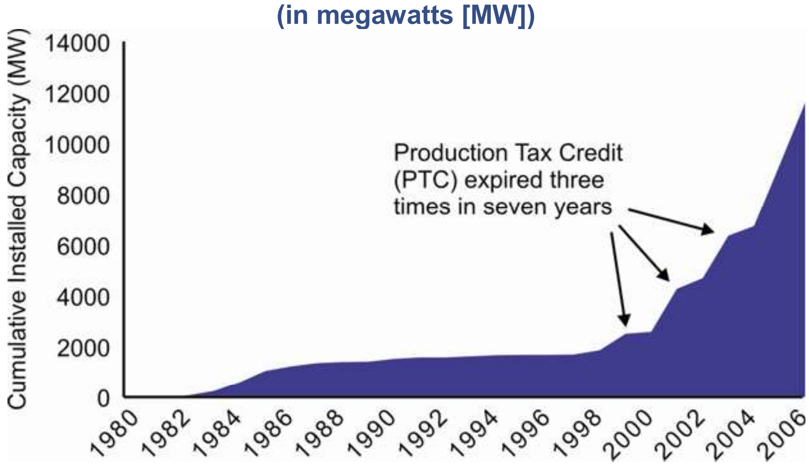


[3] The model, developed by NREL's Strategic Energy Analysis Center (SEAC), is designed to address the principal market issues related to the penetration of wind energy technologies into the electric sector. For additional information and documentation, see text box entitled "Wind Energy Deployment System Model Assumptions," Appendices A and B, and http://www.nrel.gov/analysis/winds/.

1.1.5 SETTING THE CONTEXT: TODAY'S U.S. WIND INDUSTRY

After experiencing strong growth in the mid-1980s, the U.S. wind industry hit a plateau during the electricity restructuring period in the 1990s and then regained momentum in 1999. Industry growth has since responded positively to policy incentives when they are in effect (see Figure 1-2). Today, the U.S. wind industry is growing rapidly, driven by sustained production tax credits (PTCs), rising concerns about climate change, and renewable portfolio standards (RPS) or goals in roughly 50% of the states.

Figure 1-2. Cumulative U.S. wind capacity, by year (in megawatts [MW])



U.S. turbine technology has advanced steadily to offer improved performance, and these efforts are expected to continue (see "Initiatives to Improve Wind Turbine Performance" sidebar). In 2006 alone, average turbine size increased by more than 11% over the 2005 level to an average size of 1.6 MW. In addition, average capacity factors have improved 11% over the past two years. To meet the growing demand for wind energy, U.S. manufacturers have expanded their capacity to produce and assemble the essential components. Despite this growth, U.S. components continue to represent a relatively small share of total turbine and tower materials, and U.S. manufacturers are struggling to keep pace with rising demand (Wiser & Bolinger 2007).

Initiatives to Improve Wind Turbine Performance

Avoid problems before installation

- Improve reliability of turbines and components
- Full-scale testing prior to commercial introduction
- Development of appropriate design criteria, specifications, and standards
- Validation of design tools

Monitor performance

- Monitor and evaluate turbine and wind-plant performance
- Performance tracking by independent parties
- Early identification of problems

Rapid deployment of problem resolution

- Develop and communicate problem solutions
- Focused activities with stakeholders to address critical issues (e.g., Gearbox Reliability Collaborative)

In 2005 and 2006, the United States led the world in new wind installations. By early 2007, global wind power capacity exceeded 74 GW, and U.S. wind power capacity totaled 11.6 GW. This domestic wind power has been installed across 35 states and delivers roughly 0.8% of the electricity consumed in the nation (Wiser and Bolinger 2007).

Q3

A Brief History of the U.S. Wind Industry

The U.S. wind industry got its start in California during the 1970s, when the oil shortage increased the price of electricity generated from oil. The California wind industry benefited from federal and state ITCs as well as state-mandated standard utility contracts that guaranteed a satisfactory market price for wind power. By 1986, California had installed more than 1.2 GW of wind power, representing nearly 90% of global installations at that time.

Expiration of the federal ITC in 1985 and the California incentive in 1986 brought the growth of the U.S. wind energy industry to an abrupt halt in the mid-1980s. Europe took the lead in wind energy, propelled by aggressive renewable energy policies enacted between 1974 and 1985. As the global industry continued to grow into the 1990s, technological advances led to significant increases in turbine power and productivity. Turbines installed in 1998 had an average capacity 7 to 10 times greater than that of the 1980s turbines, and the price of wind-generated electricity dropped by nearly 80% (AWEA 2007). By 2000, Europe had more than 12,000 MW of installed wind power, versus only 2,500 MW in the United States, and Germany became the new international leader.

With low natural gas prices and U.S. utilities preoccupied by industry restructuring during the 1990s, the federal production tax credit (PTC) enacted in 1992 (as part of the Energy Policy Act [EPAct]) did little to foster new wind installations until just before its expiration in June 1999. Nearly 700 MW of new wind generation were installed in the last year before the credit expired—more than in any previous 12-month period since 1985. After the PTC expired in 1999, it was extended for two brief periods, ending in 2003. It was then reinstated in late 2004. Although this intermittent policy support led to sporadic growth, business inefficiencies inherent in serving this choppy market inhibited investment and restrained market growth.

Energy Policy Act of 1992

The PTC gave power producers 1.5 cents (increased annually with inflation) for every kilowatt-hour (kWh) of electricity produced from wind during the first 10 years of operation.

To promote renewable energy systems, many states began requiring electricity suppliers to obtain a small percentage of their supply from renewable energy sources, with percentages typically increasing over time. With Iowa and Texas leading the way, more than 20 states have followed suit with RPSs, creating an environment for stable growth.

After a decade of trailing Germany and Spain, the United States reestablished itself as the world leader in new wind energy in 2005. This resurgence is attributed to increasingly supportive policies, growing interest in renewable energy, and continued improvements in wind technology and performance. The United States retained its leadership of wind development in 2006 and, because of its very large wind resources, is likely to remain a major force in the highly competitive wind markets of the future.

1.2 SCENARIO DESCRIPTION

The 20% Wind Scenario presented here would require U.S. wind power capacity to grow from 11.6 GW in 2006 to more than 300 GW over the next 23 years (see Figure 1-3). This ambitious growth could be achieved in many different ways, with varying challenges, impacts, and levels of success. The 20% Wind Scenario would require an installation rate of 16 GW per year after 2018 (see Figure 1-4). This report examines one particular scenario for achieving this dramatic growth and contrasts it to another scenario that—for analytic simplicity—assumes no wind growth after 2006. The authors recognize that U.S. wind capacity is currently growing rapidly (although from a very small base) and that wind energy technology will be a part of any future electricity generation scenario for the United States. At the same time, a great deal of uncertainty remains about the level of contribution that wind could or is likely to make. In the 2007 *Annual Energy Outlook* (EIA 2007), an additional 7 GW beyond the 2006 installed capacity of 11.6 GW is forecast by 2030.[4] Other organizations are projecting higher capacity additions, and it would be difficult to develop a "most likely" forecast given today's uncertainties. The analysis presented here sidesteps these uncertainties and contrasts some of the challenges and impacts of producing 20% of the nation's electricity from wind with a scenario in which no additional wind is added after 2006. This results in an estimate, expressed in terms of parameters, of the impacts associated with increased reliance on wind energy generation under given assumptions. The analysis was also simplified by assuming that the contributions to U.S. electricity supplies from other renewable sources of energy would remain at 2006 levels in both scenarios (see Figure A-6 for resource mix).

Figure 1-3. Required growth in U.S. capacity (GW) to implement the 20% Wind Scenario

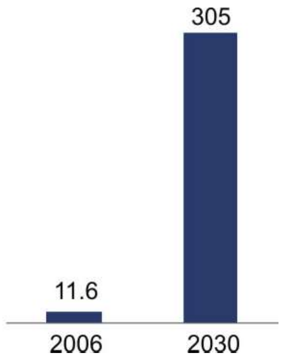
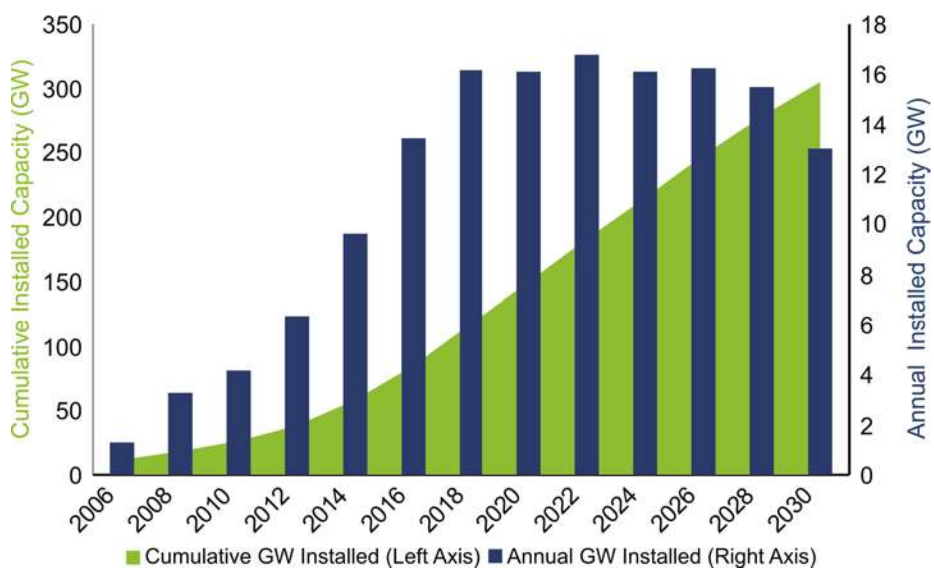


Figure 1-4. Annual and cumulative wind installations by 2030



The 20% Wind Scenario has been carefully defined to provide a base of

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[4] AEO data from 2007 were used in this report. AEO released new data in March 2008, which were not incorporated into this report. While new EIA data could change specific numbers in this report, it would not change the overall message of the report.

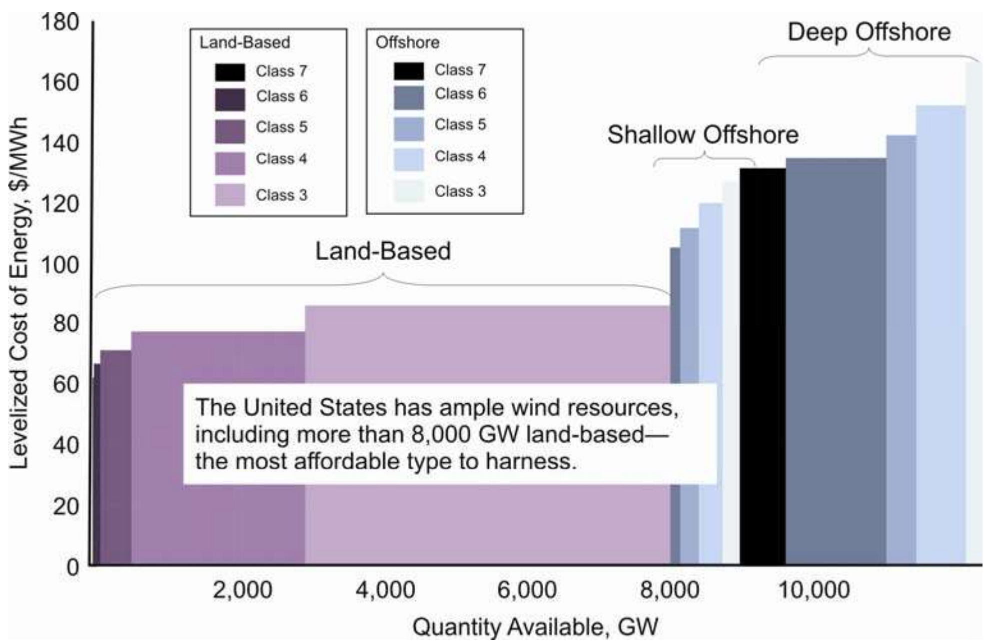
common assumptions for detailed analysis of all impact areas. Broadly stated, this 20% scenario is designed to consider incremental costs while recognizing realistic constraints and considerations (see the “Considerations in the 20% Wind Scenario” sidebar in Appendix A). Specifically, the scenario describes the mix of wind resources that would need to be captured, the geographic distribution of wind power installations, estimated land needs, the required utility and transmission infrastructure, manufacturing requirements, and the pace of growth that would be necessary.

1.2.1 WIND GEOGRAPHY

The United States possesses abundant wind resources. As shown in Figure 1-5, current “bus-bar” energy costs for wind (based on costs of the wind plant only, excluding transmission and integration costs and the PTC) vary by type of location (land-based or offshore) and by class of wind power density (higher classes offer greater productivity). Transmission and integration will add additional costs, which are discussed in Chapter 4. The nation has more than 8,000 GW of available land-based wind resources (Black & Veatch 2007) that industry estimates can be captured economically. NREL periodically classifies wind resources by wind speed, which forms the basis of the Black & Veatch study. See Appendix B for further details.

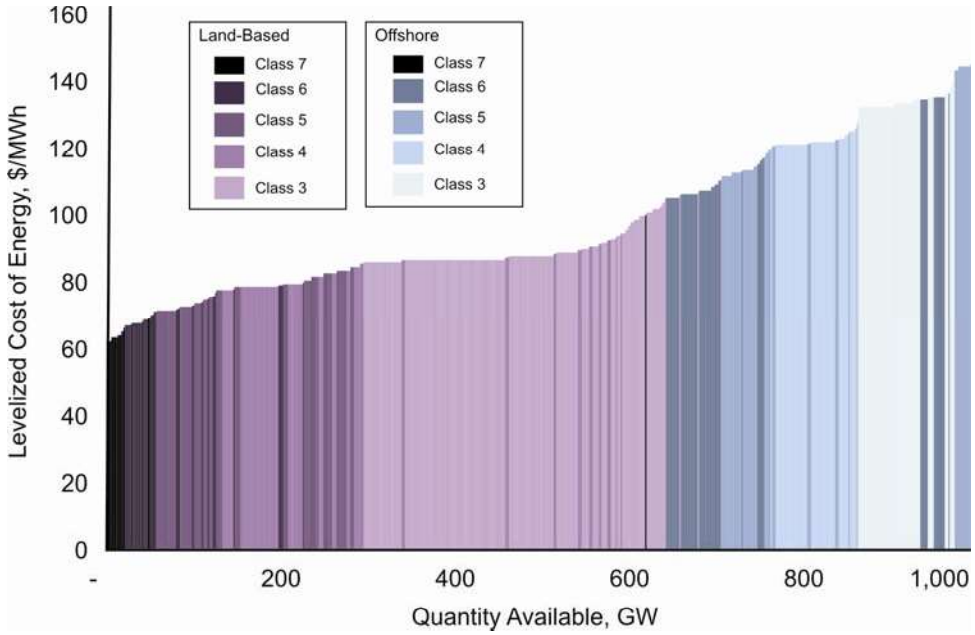
Electricity must be transmitted from where it is generated to areas of high electricity demand, using the existing transmission system or new transmission lines where necessary. As shown in Figure 1-6, the delivered cost of wind power increases when costs associated with connecting to the existing electric grid are included. The assumptions used in this report are different than EIA’s assumptions and are documented in Appendices A and B. The cost and performance assumptions of the 20% Wind Scenario are based on real market data from 2007. Cost and performance for all technologies either decrease or remain flat over time. The data suggest that as

Figure 1-5. Supply curve for wind energy—current bus-bar energy costs



Note: See Appendix B for wind technology cost and performance projections; PTC and transmission and integration costs are excluded.

Figure 1-6. Supply curve for wind energy—energy costs including connection to 10% of existing transmission grid capacity



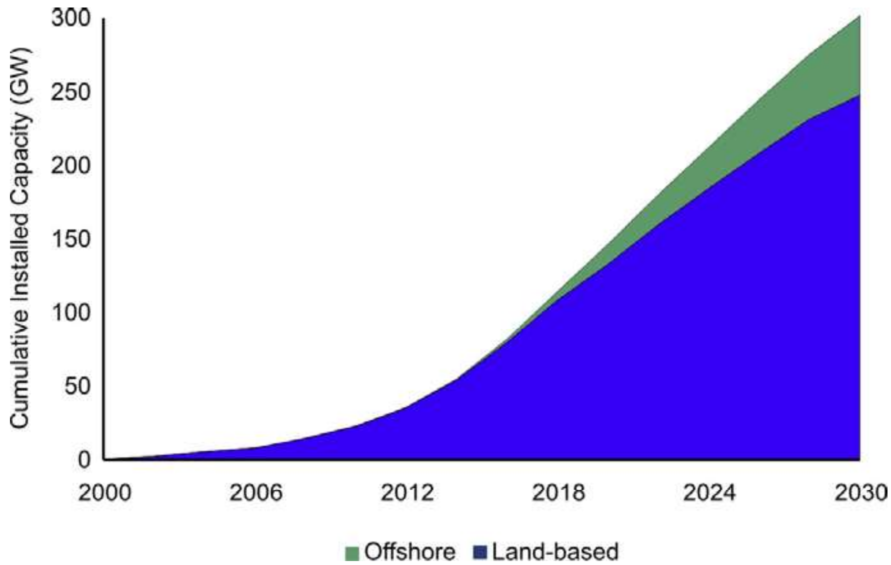
Note: See Appendix B for wind technology cost and performance projections. Excludes PTC, includes transmission costs to access existing electric transmission within 500 miles of wind resource.

much as 600 GW of wind resources could be available for $60 to $100 per megawatt-hour (MWh), including the cost of connecting to the existing transmission system. Including the PTC reduces the cost by about $20/MWh, and costs are further reduced if technology improvements in cost and performance are projected. In some cases, new transmission lines connecting high-wind resource areas to load centers could be cost-effective, and in other cases, high transmission costs could offset the advantage of land-based generation, as in the case of large demand centers along wind-rich coastlines.

NREL's WinDS model estimated the overall U.S. generation capacity expansion that is required to meet projected electricity demand growth through 2030. Both wind technology and conventional generation technology (i.e., coal, nuclear) were included in the modeling, but other renewables were not included. Readers should refer to Appendices A and B to see a more complete list of the modeling assumptions. Wind energy development for the 20% Wind Scenario optimized the total delivered costs, including future reductions in cost per kilowatt-hour for wind sites both near to and remote from demand sites from 2000 through 2030.[5] Chapter 2 presents additional discussion of wind technology potential. Of the 293 GW that would be added, the model specifies more than 50 GW of offshore wind energy (see Figure 1-7), mostly along the northeastern and southeastern seaboards.

[5] The modeling assumptions prescribed annual wind energy generation levels that reached 20% of projected demand by 2030 so as to demonstrate technical feasibility and quantify costs and impacts. Policy options that would help induce this growth trajectory were not included. It is assumed that a stable policy environment that recognizes wind's benefits could lead to growth rates that would result in the 20% Wind Scenario.

Figure 1-7. 20% cumulative installed wind power capacity required to produce 20% of projected electricity by 2030



Based on this least-cost optimization algorithm (which incorporates future cost per kilowatt-hour of wind and cost of transmission), the WinDS model estimated the wind capacity needed by state by 2030. As shown in Figure 1-8, most states would have the opportunity to develop their wind resources. Total land requirements are extensive, but only about 2% to 5% of the total would be dedicated entirely to the wind installation. In addition, the visual impacts and other siting concerns of wind energy projects must be taken into account in assessing land requirements. Chapter 5 contains additional discussion of land use and visual impacts. Again, the 20% Wind Scenario presented here is not a prediction. Figure 1-8 simply shows one way in which a 20% wind future could evolve.

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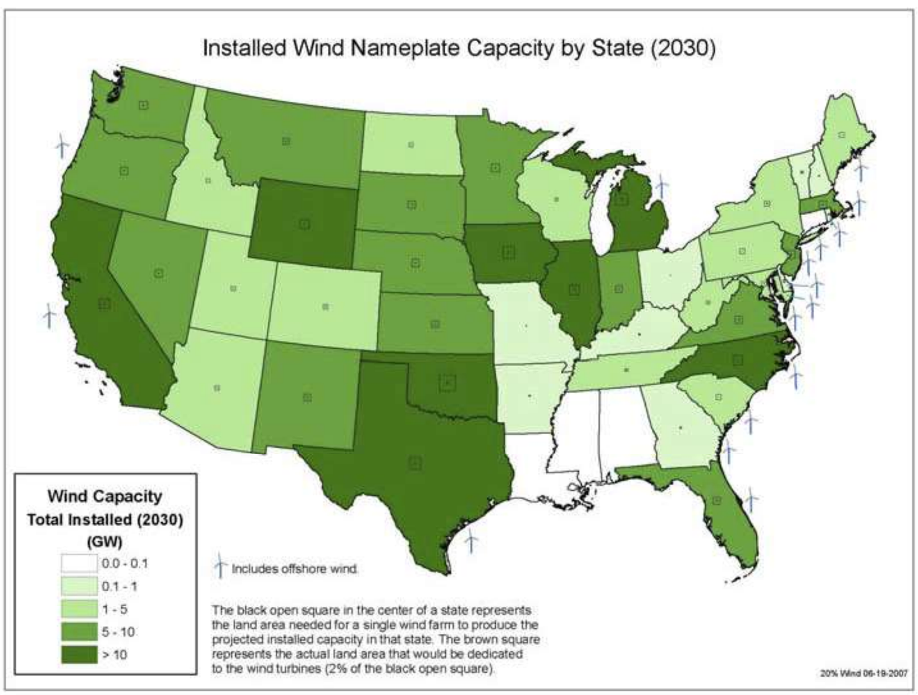
Figure 1-8. 46 states would have substantial wind development by 2030



Land Requirements

Altogether, new land-based installations would require approximately 50,000 square kilometers (km^2) of land, yet the actual footprint of land-based turbines and related infrastructure would require only about 1,000 to 2,500 km^2 of dedicated land—slightly less than the area of Rhode Island.

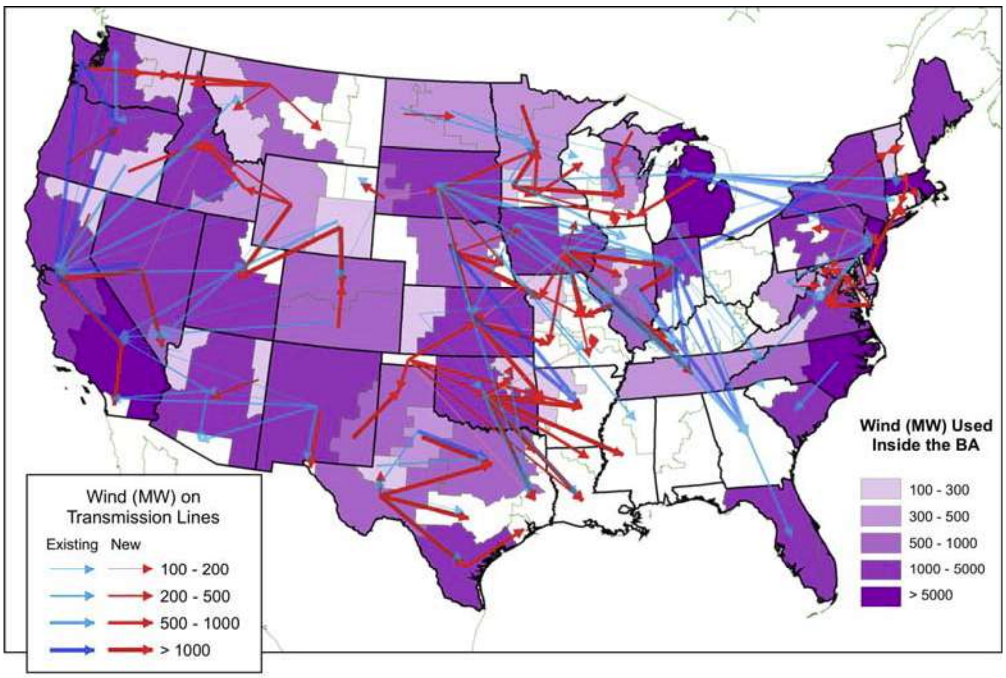
The 20% Wind Scenario envisions 251 GW of land-based and 54 GW of shallow offshore wind capacity to optimize delivered costs, which include both generation and transmission.

Wind capacity levels in each state depend on a variety of assumptions and the national optimization of electricity generation expansion. Based on the perspectives of industry experts and near-term wind development plans, wind capacity in Ohio was modified and offshore wind development in Texas was included. In reality, each state's wind capacity level will vary significantly as electricity markets evolve and state policies promote or restrict the energy production of electricity from wind and other renewable and conventional energy sources.

1.2.2 WIND POWER TRANSMISSION AND INTEGRATION

Development of 293 GW of new wind capacity would require expanding the U.S. transmission grid in a manner that not only accesses the best wind resource regions of the country but also relieves current congestion on the grid, including new transmission lines to deliver wind power to electricity consumers. Figure 1-9 conceptually illustrates the optimized use of wind resources within the local areas as well as the transmission of wind-generated electricity from high-resource areas to high-demand centers. This data was generated by the WinDS model (given prescribed constraints). The figure does not represent proposals for specific transmission lines.

Figure 1-9. All new electricity generation including wind energy would require expansion of U.S. transmission by 2030

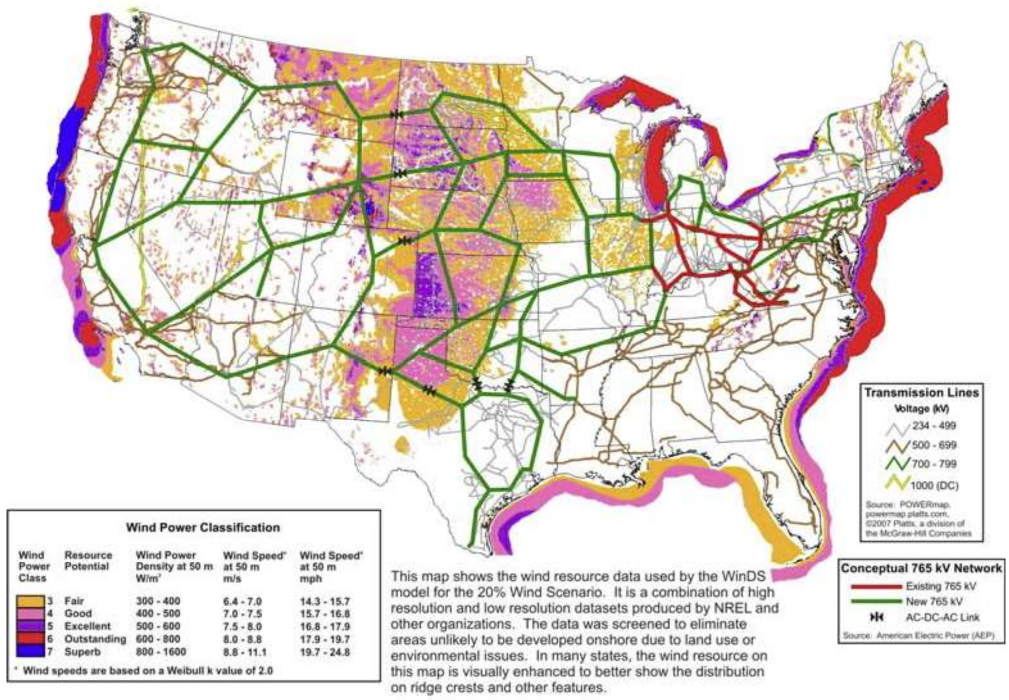


Total Between Balancing Areas Transfer >= 100 MW (all power classes, land-based and offshore) in 2030.
Wind power can be used locally within a Balancing Area (BA), represented by purple shading, or transferred out of the area on new or existing transmission lines, represented by red or blue arrows. Arrows originate and terminate at the centroid of the BA for visualization purposes; they do not represent physical locations of transmission lines.

Figure 1-10 displays transmission needs in the form of one technically feasible transmission grid as a 765 kV overlay. A complete discussion of transmission issues can be found in Chapter 4.

Until recently, concerns had been prevalent in the electric utility sector about the difficulty and cost of dealing with the variability and uncertainty of energy production from wind plants and other weather-driven renewable technologies. But utility engineers in some parts of the United States now have extensive experience with wind plant impacts, and their analyses of these impacts have helped to reduce these concerns. As discussed in detail in Chapter 4, wind's variability is being accommodated, and given optimistic assumptions, studies suggest the cost impact could be as little as the current level—10% or less of the value of the wind energy generated.

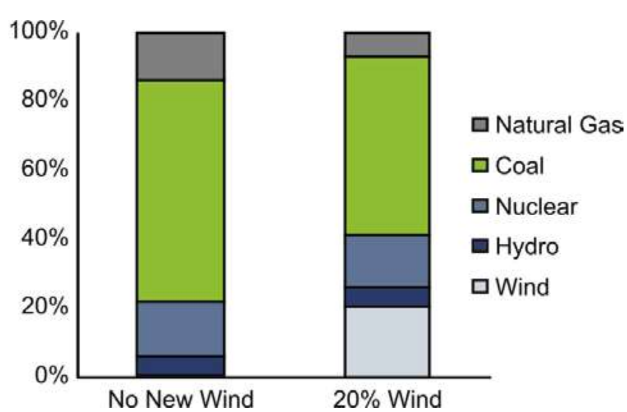
Figure 1-10. Conceptual transmission plan to accommodate 400 GW of wind energy (AEP 2007)



1.2.3 ELECTRICAL ENERGY MIX

The U.S. Energy Information Administration (EIA) estimates that U.S. electricity demand will grow by 39% from 2005 to 2030, reaching 5.8 billion MWh by 2030. The 20% Wind Scenario would require delivery of nearly 1.16 billion MWh of wind energy in 2030, altering U.S. electricity generation as shown in Figure 1-11. In this scenario, wind would supply enough energy to displace about 50% of electric utility natural gas consumption and 18% of coal consumption by 2030. This amounts to an 11% reduction in natural gas across all industries. (Gas-fired generation would probably be displaced first, because it typically has a higher cost.)

Figure 1-11. U.S. electrical energy mix



The increased wind development in this scenario could reduce the need for new coal and combined cycle natural gas capacity, but would increase the need for additional combustion turbine natural gas capacity to maintain electric system reliability. These units, though, would be run only as needed.[6]

1.2.4 PACE OF NEW WIND INSTALLATIONS

Manufacturing capacity would require time to ramp up enough to support rapid growth in new U.S. wind installations. The 20% Wind Scenario estimates that the installation rate would need to

[6] Appendix A presents a full analysis of changes in the capacity mix and energy generation under the 20% Wind Scenario.

increase from installing 3 GW per year in 2006 to more than 16 GW per year by 2018 and to continue at roughly that rate through 2030, as seen in Figure 1-4. This increase in installation rate, although quite large, is comparable to the recent annual installation rate of natural gas units, which totaled more than 16 GW in 2005 alone (EIA 2005).

The assumptions of the 20% Wind Scenario form the foundation for the technical analyses presented in the remaining chapters. This overview is provided as context for the potential impacts and technical challenges discussed in the next sections.

Wind vs. Traditional Electricity Generation

Wind power avoids several of the negative effects of traditional electricity generation from fossil fuels:

- Emissions of mercury or other heavy metals into the air
- Emissions associated with extracting and transporting fuels
- Lake and streambed acidification from acid rain or mining
- Water consumption associated with mining or electricity generation
- Production of toxic solid wastes, ash, or slurry
- Greenhouse gas (GHG) emissions

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1.3 IMPACTS

The 20% Wind Scenario presented here offers potentially positive impacts in terms of greenhouse gas (GHG) reductions, water conservation, and energy security, as compared to the base case of no wind growth in this analysis. However, tapping this resource at this level would entail large front-end capital investments to install wind capacity and expanded transmission systems. The impacts described in this section are based largely on the analytical tools and methodology discussed in detail in Appendices A, B, and C.

20% Wind Scenario: Projected Impacts

- **Environment:** Avoids air pollution and reduces GHG emissions; reduces electric sector CO_2 emissions by 825 million metric tons annually
- **Water savings:** Reduces cumulative water use in the electric sector by 8% (4 trillion gallons)
- **U.S. energy security:** Diversifies electricity portfolio and represents an indigenous energy source with stable prices not subject to fuel volatility
- **Energy consumers:** Potentially reduces demand for fossil fuels, in turn reducing fuel prices and stabilizing electricity rates
- **Local economics:** Creates new income source for rural landowners and tax revenues for local communities in wind development areas
- **American workers:** Generates well-paying jobs in sectors that support wind development, such as manufacturing, engineering, construction, transportation, and financial services; new manufacturing will cause significant growth in wind industry supply chain (see Appendix C)

Wind power would be a critical part of a broad and near-term strategy to substantially reduce air pollution, water pollution, and global climate change associated with traditional generation technologies (see "Wind vs. Traditional Electricity Generation" sidebar). As a domestic energy resource, wind power would also stabilize and diversify national energy supplies.

1.3.1 GREENHOUSE GAS REDUCTIONS

Supplying 20% of U.S. electricity from wind could reduce annual electric sector carbon dioxide (CO_2) emissions by 825 million metric tons by 2030.

20% Wind Scenario: Major Challenges

- Investment in the nation's transmission system, so that the power generated is delivered to urban centers that need the increased supply;
- Larger electric load balancing areas, in tandem with better regional planning, so that regions can depend on a diversity of generation sources, including wind power;
- Continued reduction in wind capital costs and improvement in turbine performance through technology advancement and improved manufacturing capabilities; and
- Addressing potential concerns about local siting, wildlife, and environmental issues within the context of generating electricity.

The threat of climate change and the growing attention paid to it are helping to position wind power as an increasingly attractive option for new power generation. U.S. electricity demand is growing rapidly, and cleaner power sources (e.g., renewable energy) and energy-saving practices (i.e., energy efficiency) could help meet much of the new demand while reducing GHG emissions. Today, wind energy represents approximately 35% of new capacity additions (AWEA 2008). Greater use of wind energy, therefore, presents an opportunity for reducing emissions today as the nation develops additional clean power options for tomorrow.

Concerns about climate change have spurred many industries, policy makers, environmentalists, and utilities to call for reductions in GHG emissions. Although the cost of reducing emissions is uncertain, the most affordable near-term strategy likely involves wider deployment of currently available energy efficiency and clean energy technologies. Wind power is one of the potential supply-side solutions to the climate change problem (Socolow and Pacala 2006).

GHG Reduction

Under the 20% Wind Scenario, a cumulative total of 7,600 million metric tons of CO_2 emissions would be avoided by 2030, and more than 15,000 million metric tons of CO_2 emissions would be avoided through 2050.

Governments at many levels have enacted policies to actively support clean electricity generation, including the renewable energy PTC and state RPS. A growing number of energy and environmental organizations are calling for expanded wind and other renewable power deployment to try to reduce society's carbon footprint.

According to EIA, The United States annually emits approximately 6,000 million metric tons of CO_2. These emissions are expected to increase to nearly 7,900 million metric tons by 2030, with the electric power sector accounting for approximately 40% of the total (EIA 2007). As shown in Figure 1-12, based on the analysis completed for this report, generating 20% of U.S. electricity from wind could avoid approximately 825 million metric tons of CO_2 emissions in the electric sector in 2030. The 20% Wind Scenario would also reduce *cumulative* emissions from the electric sector through that same year by more than 7,600 million metric tons of CO_2 (2,100 million metric tons of carbon equivalent).[7] See Figures 1-12 and 1-13 . In general, CO_2 emission reductions are not only a wind energy benefit but could be achieved under other energy-mix scenarios.

The Fourth Assessment Report of the United Nations Environment Program and World Meteorological Organization's Intergovernmental Panel on Climate Change (IPCC) notes that "Renewable energy generally has a positive effect on energy

[7] CO_2 can be converted to carbon equivalent by multiplying by 12/44. Appendix A presents results in carbon equivalent, not CO_2. Because it assumes a higher share of coal-fired generation, the WinDS model projects higher CO_2 emissions than the EIA model.

Figure 1-12. Annual CO_2 emissions avoided (vertical bars) would reach 825 million metric tons by 2030

The cumulative avoided emissions by 2030 would total 7,600 million metric tons.

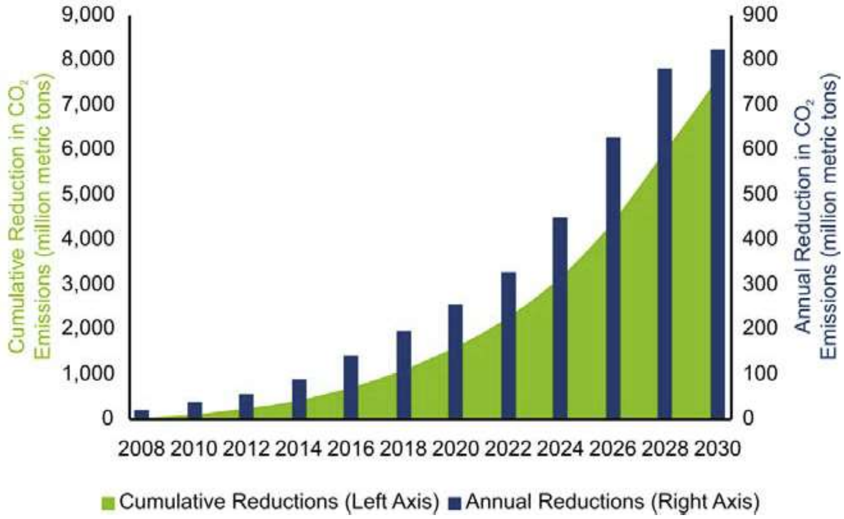
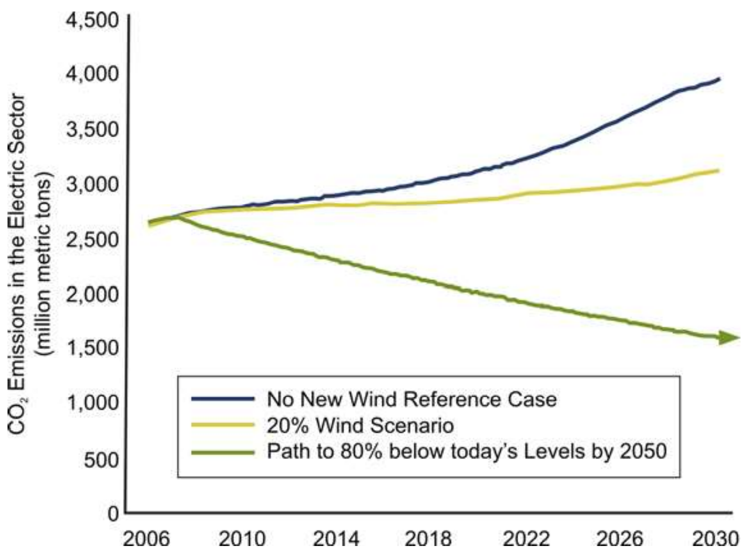


Figure 1-13. CO_2 emissions from the electricity sector



security, employment, and air quality. Given costs relative to other supply options, renewable electricity can have a 30% to 35% share of the total electricity supply in 2030. Deployment of low-GHG (greenhouse gas) emission technologies would be required for achieving stabilization and cost reductions" (IPCC 2007).

More than 30 U.S. states have created climate action plans. In addition, the Regional Greenhouse Gas Initiative (RGGI) is a 10-state collaborative in the Northeast to address CO_2 emissions. All of these state and regional efforts include wind energy as part of a portfolio strategy to reduce overall emissions from energy production (RGGI 2006).

Because wind turbines typically have a service life of at least 20 years and transmission lines can last more than 50 years, investments in achieving 20% wind power by 2030 could continue to supply clean energy through at least 2050. As a result, the cumulative climate change impact of achieving 20% wind power could grow to more than 15,000 million metric tons of CO_2 emissions avoided by mid-century (4,182 million metric tons of carbon equivalent).

The 20% Wind Scenario constructed here would displace a significant amount of fossil fuel generation. According to the WinDS model, by 2030, wind generation is projected to displace 50% of electricity generated from natural gas and 18% of that generated from coal. The displacement of coal is of particular interest because it provides a comparatively higher carbon emissions reduction opportunity. Recognizing that coal power will continue to play a major role in future electricity generation, a large increase in total wind capacity could potentially defer the need to build some new coal capacity, avoiding or postponing the associated increases in carbon emissions. Current DOE projections anticipate construction of approximately 140 GW of new coal plant capacity by 2030 (EIA 2007); the 20% Wind Scenario could avoid construction of more than 80 GW of new coal capacity.[8]

Wind energy that displaces fossil fuel generation can also help meet existing regulations for emissions of conventional pollutants, including sulfur dioxide, nitrogen oxides, and mercury.

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1.3.2 Water Conservation

The 20% scenario would potentially reduce cumulative water consumption in the electric sector by 8% (or 4 trillion gallons) from 2007 through 2030—significantly reducing water consumption in the arid states of the interior West. In 2030, annual water consumption in the electric sector would be reduced by 17%.

> **Wind Reduces Vulnerability**
>
> Continued reliance on natural gas for new power generation is likely to put the United States in growing competition in world markets for liquefied natural gas (LNG)—some of which will come from Russia, Qatar, Iran, and other nations in less-than-stable regions.

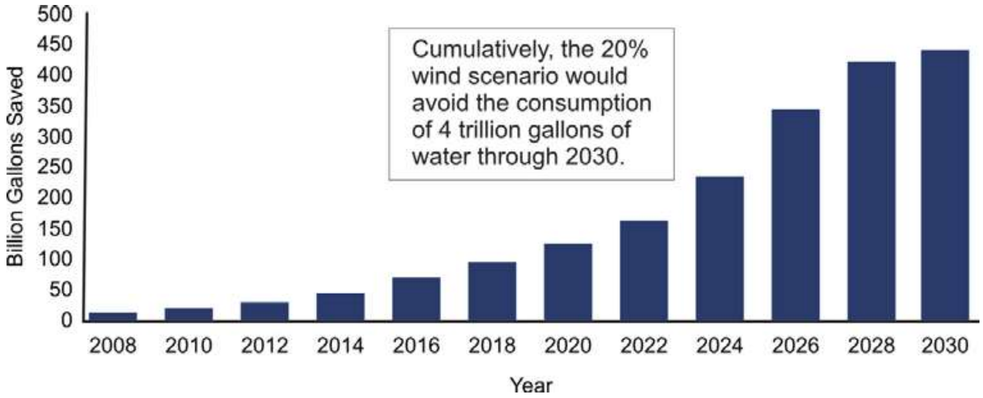
Water scarcity is a significant problem in many parts of the United States. Even so, few U.S. citizens realize that electricity generation accounts for nearly 50% of all water withdrawals in the nation, with irrigation withdrawals coming in second at 34% (USGS 2005). Water is used for the cooling of natural gas, coal, and nuclear power plants and is an increasing part of the challenge in developing those resources.

Although a significant portion of the water withdrawn for electricity production is recycled back through the system, approximately 2% to 3% of the water withdrawn is consumed through evaporative losses. Even this small fraction adds up to approximately 1.6 to 1.7 trillion gallons of water consumed for power generation each year.

As additional wind generation displaces fossil fuel generation, each megawatt-hour generated by wind could save as much as 600 gallons of water that would otherwise

[8] Carbon mitigation policies were not modeled in either the 20% Wind or No New Wind Scenarios, which results in conventional generation mixes typical of current generation capacity. Under carbon mitigation scenarios, additional technologies could be implemented to reduce the need for conventional generation technology (see Appendix A).

Figure 1-14. National water savings from the 20% Wind Scenario



be lost to fossil plant cooling.[9] Because wind energy generation uses a negligible amount of water, the 20% Wind Scenario would avoid the consumption of 4 trillion gallons of water through 2030, a cumulative reduction of 8%, with annual reductions through 2030 shown in Figure 1-14. The annual savings in 2030 is approximately 450 billion gallons. This savings would reduce the expected annual water consumption for electricity generation in 2030 by 17%. The projected water savings are dependent on a future generation mix, which is discussed further in Appendix A.

Based on the WinDS modeling results, nearly 30% of the projected water savings from the 20% Wind Scenario would occur in western states, where water resources are particularly scarce. The Western Governors Association (WGA) highlights this concern in its Clean and Diversified Energy Initiative, which recognizes increased water consumption as a key challenge in accommodating rapid growth in electricity demand. In its 2006 report on water needs, the WGA states that "difficult political choices will be necessary regarding future economic and environmental uses of water and the best way to encourage the orderly transition to a new equilibrium" (WGA 2006).

1.3.3 Energy Security and Stability

There is broad and growing recognition that the nation should diversify its energy portfolio so that a supply disruption affecting a single energy source will not significantly disrupt the national economy. Developing domestic energy sources with known and stable costs would significantly improve U.S. energy stability and security.

When electric utilities have a Power Purchase Agreement or own wind turbines, the price of energy is expected to remain relatively flat and predictable for the life of the wind project, given that there are no fuel costs and assuming that the machines are well maintained. In contrast, a large part of the cost of coal- and gas-fired electricity is in the fuel, for which prices are often volatile and unpredictable. Fuel price risks reduce security and stability for U.S. manufacturers and consumers, as well as for the U.S. economy as a whole. Even small reductions in the amount of energy available or changes in the price of fuel can cause large economic disruptions across the nation. This capacity to disrupt was clearly illustrated by the 1973 embargo imposed by the Organization of Arab Petroleum Exporting Countries (the "Arab oil embargo"); the 2000–2001 California electricity market problems; and the gasoline

[9] See Appendix A for specific assumptions.

and natural gas shortages and price spikes that followed the 2005 hurricane damage to oil refinery and natural gas processing facilities along the Gulf Coast.

Using wind energy increases security and stability by diversifying the national electricity portfolio. Just as those investing for retirement are advised to diversify investments across companies, sectors, and stocks and bonds, diversification of electricity supplies helps distribute the risks and stabilize rates for electricity consumers.

Wind energy reduces reliance on foreign energy sources from politically unstable regions. As a domestic energy source, wind requires no imported fuel, and the turbine components can be either produced on U.S. soil or imported from any friendly nation with production capabilities.

Energy security concerns for the electric industry will likely increase in the foreseeable future as natural gas continues to be a leading source of new generation supply. With declining domestic natural gas sources, future natural gas supplies are expected to come in the form of liquefied natural gas (LNG) imported on tanker ships. U.S. imports of LNG could quadruple by 2030 (EIA 2007). Almost 60% of uncommitted natural gas reserves are in Iran, Qatar, and Russia. These countries, along with others in the Middle East, are expected to be major suppliers to the global LNG market. Actions by those sources can disrupt international energy markets and thus have indirect adverse effects on our economy. Additional risks arise from competition for these resources caused by the growing energy demands of China, India, and other developing nations. According to the WinDS model results, under the 20% Wind Scenario, wind energy could displace approximately 11% of natural gas consumption, which is equivalent to 60% of expected LNG imports in 2030.[10] This displacement would reduce the nation's energy vulnerability to uncertain natural gas supplies. See Appendix A for gas demand reduction assumptions and calculations.

Continued reliance on fossil energy sources exposes the nation to price risks and supply uncertainties. Although the electric sector does not rely heavily on petroleum, which represents one of the nation's biggest energy security threats, diversifying the electric generation mix with increased domestic renewable energy would still enhance national energy security by increasing energy diversity and price stability.

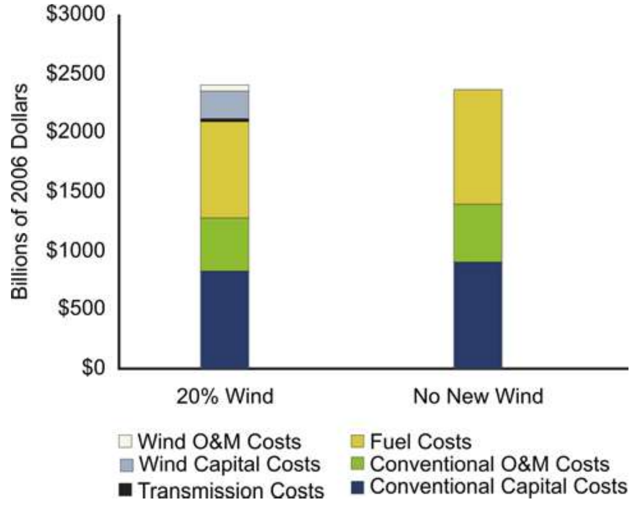
1.3.4 Cost of the 20% Wind Scenario

The overall economic cost of the 20% Wind Scenario accrues mainly from the incremental costs of wind energy relative to other generation sources. This is impacted by the assumptions behind the scenario, listed in Table A-1. Also, some incremental transmission would be required to connect wind to the electric power system. This transmission investment would be in addition to the significant investment in the electric grid that will be needed to serve continuing load growth, whatever the mix of new generation. The market cost of wind energy remains higher than that of conventional energy sources in many areas across the country. In addition, the transmission grid would have to be expanded and upgraded in wind-rich areas and across the existing system to deliver wind energy to many demand centers. An integrated approach to expanding the transmission system would need to include furnishing access to wind resources as well as meeting other system needs.

[10] Compared to consumption of the high price scenario of EIA (2007), used in this report.

Compared to other generation sources, the 20% Wind Scenario entails higher initial capital costs (to install wind capacity and associated transmission infrastructure) in many areas, yet offers lower ongoing energy costs for operations, maintenance, and fuel. Given the optimistic cost and performance assumptions of wind and

Figure 1-15. Incremental investment cost of 20% wind is modest; a difference of 2%



conventional energy sources (detailed in Appendix B), the 20% Wind Scenario could require an incremental investment of as little as $43 billion net present value (NPV) more than the base-case scenario involving no new wind power generation (No New Wind Scenario). This would represent less than 0.06 cents (6 one-hundredths of 1 cent) per kilowatt-hour of total generation by 2030, or roughly 50 cents per month per household. Figure 1-15 shows this cost comparison. The base-case costs are calculated under the assumption of no major changes in fuel availability or environmental restrictions. In this scenario, the cost differential would be about 2% of a total NPV expenditure exceeding $2 trillion.

This analysis is intended to identify the incremental cost of pursuing the 20% Wind Scenario. In regions where the capital costs of the 20% Wind Scenario exceed those of building little or no additional wind capacity, the differential could be offset by the operating costs and benefits discussed earlier. For example, even though Figure 1-15 shows that under optimistic assumptions, the 20% Wind Scenario could increase total capital costs by nearly $197 billion, most of those costs would be offset by the nearly $155 billion in decreased fuel expenditures, resulting in a net incremental cost of approximately $43 billion in NPV. These monetary costs do not reflect other potential offsetting positive impacts.

As estimated by the NREL WinDS model, given optimistic assumptions, the specific cost of the proposed transmission expansion for the 20% Wind Scenario is $20 billion in NPV. The actual required grid investment could also involve significant costs for permitting delays, construction of grid extensions to remote areas with wind resources, and investments in advanced grid controls, integration, and training to enable regional load balancing of wind resources.

The total installed costs for wind plants include costs associated with siting and permitting of these plants. It has become clear that wind power expansion would require careful, logical, and fact-based consideration of local and environmental concerns, allowing siting issues to be addressed within a broad risk framework. Experience in many regions has shown that this can be done, but efficient, streamlined procedures will likely be needed to enable installation rates in the range of 16 GW per year. Chapter 5 covers these issues in more detail.

1.4 Conclusion

There are significant costs, challenges, and impacts associated with the 20% Wind Scenario presented in this report. There are also substantial positive impacts from wind power expansion on the scale and pace described in this chapter that are not likely to be realized in a business-as-usual future. Achieving the 20% Wind Scenario would involve a major national commitment to clean, domestic energy sources with minimal emissions of GHGs and other environmental pollutants.

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Chapter 2. Wind Turbine Technology

Today's wind technology has enabled wind to enter the electric power mainstream. Continued technological advancement would be required under the 20% Wind Scenario.

2.1 INTRODUCTION

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Current turbine technology has enabled wind energy to become a viable power source in today's energy market. Even so, wind energy provides approximately 1% of total U.S. electricity generation. Advancements in turbine technology that have the potential to increase wind energy's presence are currently being explored. These areas of study include reducing capital costs, increasing capacity factors, and mitigating risk through enhanced system reliability. With sufficient research, development, and demonstration (RD&D), these new advances could potentially have a significant impact on commercial product lines in the next 10 years.

A good parallel to wind energy evolution can be derived from the history of the automotive industry in the United States. The large-scale production of cars began with the first Model T production run in 1910. By 1940, after 30 years of making cars and trucks in large numbers, manufacturers had produced vehicles that could reliably move people and goods across the country. Not only had the technology of the vehicle improved, but the infrastructure investment in roads and service stations made their use practical. Yet 30 years later, in 1970, one would hardly recognize the vehicles or infrastructure as the same as those in 1940. Looking at the changes in automobiles produced over that 30-year span, we see how RD&D led to the continuous infusion of modern electronics; improved combustion and manufacturing processes; and ultimately, safer, more reliable cars with higher fuel efficiency. In a functional sense, wind turbines now stand roughly where the U.S. automotive fleet stood in 1940. Gradual improvements have been made in the past 30 years over several generations of wind energy products. These technology advances enable today's turbines to reliably deliver electricity to the grid at a reasonable cost.

Through continued RD&D and infrastructure development, great strides will be made to produce even more advanced machines supporting future deployment of wind power technology. This chapter describes the status of wind technology today and provides a brief history of technology development over the past three decades. Prospective improvements to utility-scale land-based wind turbines as well as offshore wind technology are discussed. Distributed wind technology [100 kilowatts (kW) or less] is also addressed in this chapter.

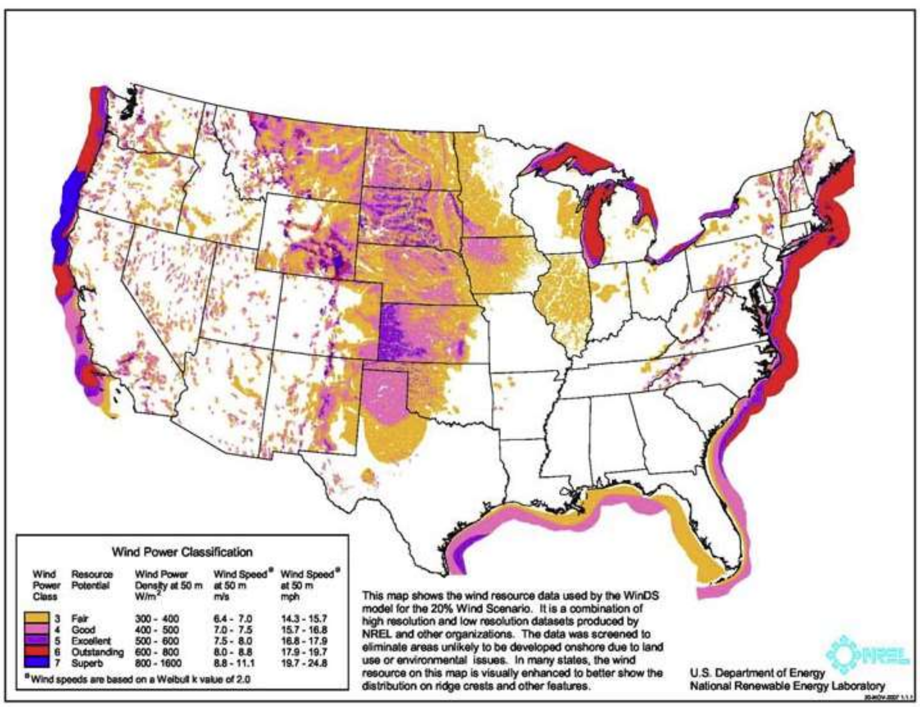
2.2 TODAY'S COMMERCIAL WIND TECHNOLOGY

Beginning with the birth of modern wind-driven electricity generators in the late 1970s, wind energy technology has improved dramatically up to the present. Capital costs have decreased, efficiency has increased, and reliability has improved. High-quality products are now routinely delivered by major suppliers of turbines around the world, and complete wind generation plants are being engineered into the grid infrastructure to meet utility needs. In the 20% Wind Scenario outlined in this report, it is assumed that capital costs would be reduced by 10% over the next two decades, and capacity factors would be increased by about 15% (corresponding to a 15% increase in annual energy generation by a wind plant).

2.2.1 WIND RESOURCES

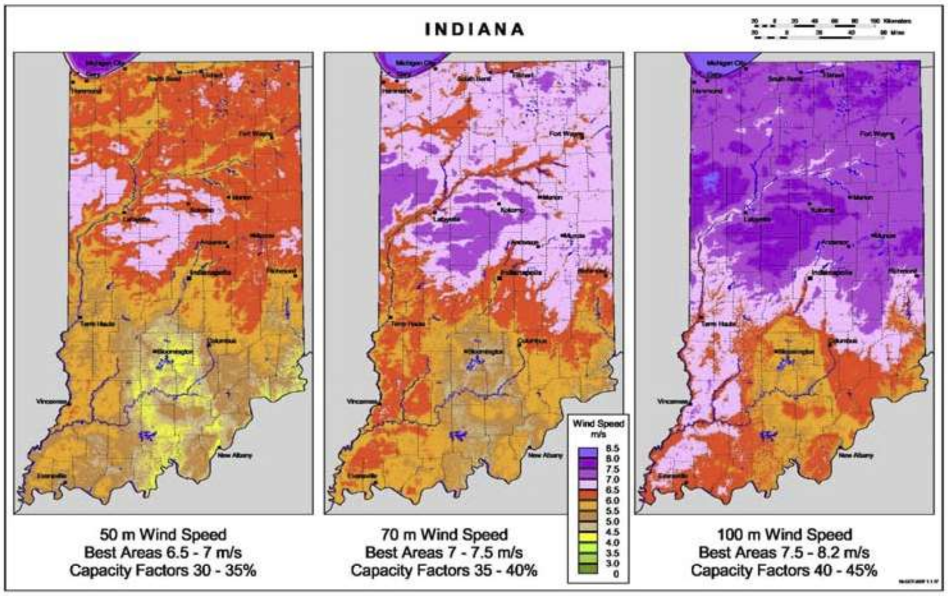
Wind technology is driven by the nature of the resource to be harvested. The United States, particularly the Midwestern region from Texas to North Dakota, is rich in wind energy resources as shown in Figure 2-1, which illustrates the wind resources measured at a 50-meter (m) elevation. Measuring potential wind energy generation at a 100-m elevation (the projected operating hub height of the next generation of modern turbines) greatly increases the U.S. land area that could be used for wind deployment, as shown in Figure 2-2 for the state of Indiana. Taking these measurements into account, current U.S. land-based and offshore wind resources are estimated to be sufficient to supply the electrical energy needs of the entire country several times over. For a description of U.S. wind resources, see Appendix B.

Figure 2-1. The wind resource potential at 50 m above ground on land and offshore



Identifying the good wind potential at high elevations in states such as Indiana and off the shore of both coasts is important because it drives developers to find ways to harvest this energy. Many of the opportunities being pursued through advanced

Figure 2-2. Comparison of the wind energy resource at 50 m, 70 m, and 100 m for Indiana



technology are intended to achieve higher elevations, where the resource is much greater, or to access extensive offshore wind resources.

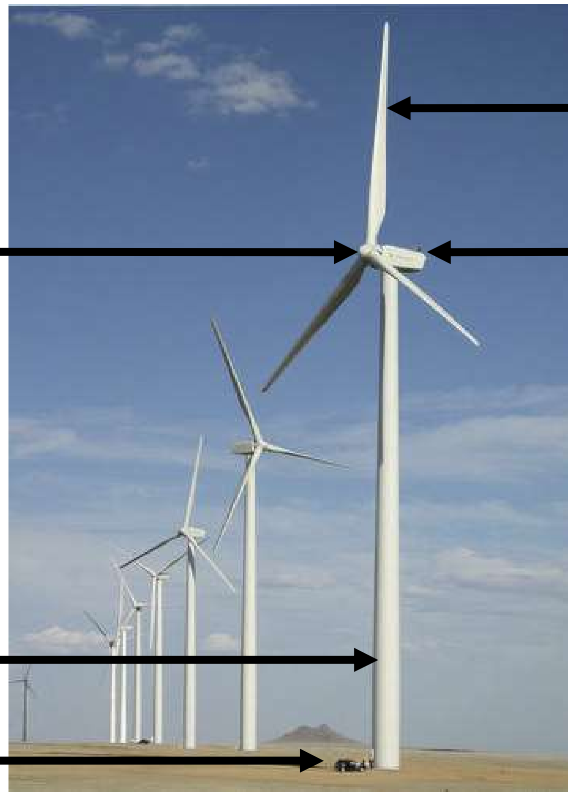
Q8

2.2.2 Today's Modern Wind Turbine

Modern wind turbines, which are currently being deployed around the world, have three-bladed rotors with diameters of 70 m to 80 m mounted atop 60-m to 80-m towers, as illustrated in Figure 2-3. Typically installed in arrays of 30 to 150 machines, the average turbine installed in the United States in 2006 can produce approximately 1.6 megawatts (MW) of electrical power. Turbine power output is controlled by rotating the blades around their long axis to change the angle of attack with respect to the relative wind as the blades spin around the rotor hub. This is called controlling the blade pitch. The turbine is pointed into the wind by rotating the nacelle around the tower. This is called controlling the yaw. Wind sensors on the nacelle tell the yaw controller where to point the turbine. These wind sensors, along with sensors on the generator and drivetrain, also tell the blade pitch controller how to regulate the power output and rotor speed to prevent overloading the structural components. Generally, a turbine will start producing power in winds of about 5.36 m/s and reach maximum power output at about 12.52 m/s–13.41 m/s. The turbine will pitch or feather the blades to stop power production and rotation at about 22.35 m/s. Most utility-scale turbines are upwind machines, meaning that they operate with the blades upwind of the tower to avoid the blockage created by the tower.

The amount of energy in the wind available for extraction by the turbine increases with the cube (the third power) of wind speed; thus, a 10% increase in wind speed creates a 33% increase in available energy. A turbine can capture only a portion of this cubic increase in energy, though, because power above the level for which the electrical system has been designed, referred to as the rated power, is allowed to pass through the rotor.

Figure 2-3. A modern 1.5-MW wind turbine installed in a wind power plant



In general, the speed of the wind increases with the height above the ground, which is why engineers have found ways to increase the height and the size of wind turbines while minimizing the costs of materials. But land-based turbine size is not expected to grow as dramatically in the future as it has in the past. Larger sizes are physically possible; however, the logistical constraints of transporting the components via highways and of obtaining cranes large enough to lift the components present a major economic barrier that is difficult to overcome. Many turbine designers do not expect the rotors of land-based turbines to become much larger than about 100 m in diameter, with corresponding power outputs of about 3 MW to 5 MW.

2.2.3 Wind Plant Performance and Price

The performance of commercial turbines has improved over time, and as a result, their capacity factors have slowly increased. Figure 2-4 shows the capacity factors at commercial operation dates (CODs) ranging from 1998 to 2005. The data show that turbines in the Lawrence Berkeley National Laboratory (Berkeley Lab) database (Wiser and Bolinger 2007) that began operating commercially before 1998 have an average capacity factor of about 22%. The turbines that began commercial operation after 1998, however, show an increasing capacity factor trend, reaching 36% in 2004 and 2005.

The cost of wind-generated electricity has dropped dramatically since 1980, when the first commercial wind plants began operating in California. Since 2003, however, wind energy prices have increased. Figure 2-5 (Wiser and Bolinger 2007)

Figure 2-4. Turbine capacity factor by commercial operation date (COD) using 2006 data

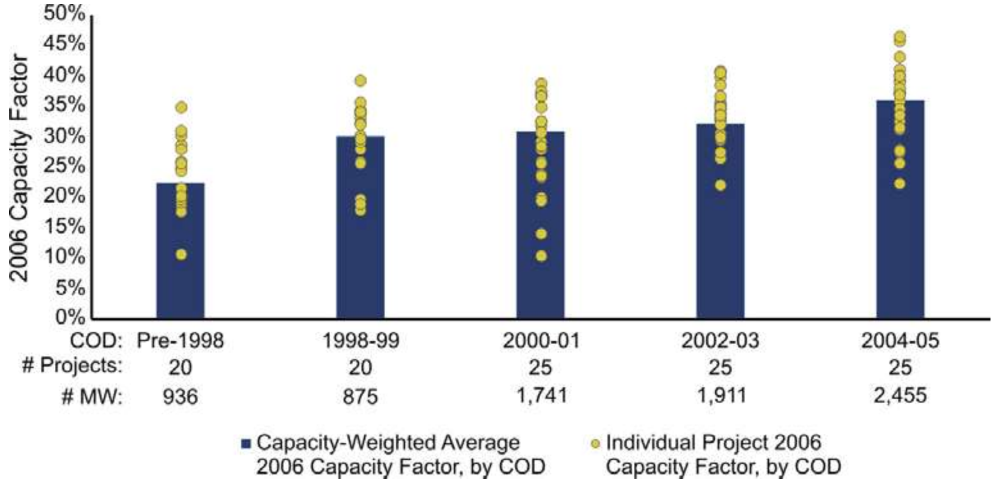
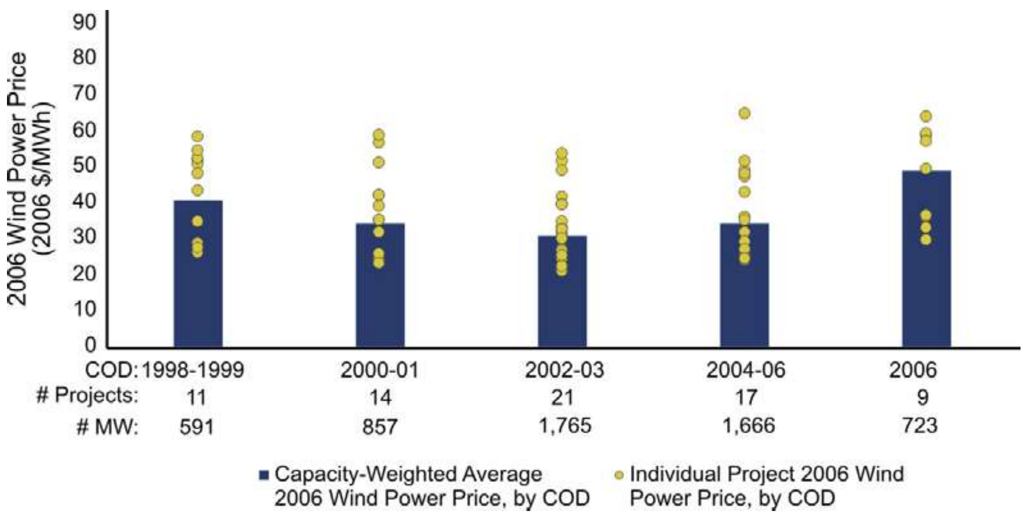


Figure 2-5. Wind energy price by commercial operation date (COD) using 2006 data



shows that in 2006 the price paid for electricity generated in large wind farms was between 3.0 and 6.5 cents/kilowatt-hour (kWh), with an average near 5 cents/kWh (1 cent/kWh = $10/megawatt-hour [MWh]). This price includes the benefit of the federal production tax credit (PTC), state incentives, and revenue from the sale of any renewable energy credits.

Wind energy prices have increased since 2002 for the following reasons (Wiser and Bolinger 2007):

- Shortages of turbines and components, resulting from the dramatic recent growth of the wind industry in the United States and Europe
- The weakening U.S. dollar relative to the euro (many major turbine components are imported from Europe, and there are relatively few wind turbine component manufacturers in the United States)

2

- A significant rise in material costs, such as steel and copper, as well as transportation fuels over the last three years
- The on-again, off-again cycle of the wind energy PTC (uncertainty hinders investment in new turbine production facilities and encourages hurried and expensive production, transportation, and installation of projects when the tax credit is available).

Expected future reductions in wind energy costs would come partly from expected investment in the expansion of manufacturing volume in the wind industry. In addition, a stable U.S. policy for renewable energy and a heightened RD&D effort could also lower costs.

2.2.4 Wind Technology Development

Until the early 1970s, wind energy filled a small niche market, supplying mechanical power for grinding grain and pumping water, as well as electricity for rural battery charging. With the exception of battery chargers and rare experiments with larger electricity-producing machines, the windmills of 1850 and even 1950 differed very little from the primitive devices from which they were derived. Increased RD&D in the latter half of the twentieth century, however, greatly improved the technology.

In the 1980s, the practical approach of using low-cost parts from agricultural and boat-building industries produced machinery that usually worked, but was heavy, high-maintenance, and grid-unfriendly. Little was known about structural loads caused by turbulence, which led to the frequent and early failure of critical parts, such as yaw drives. Additionally, the small-diameter machines were deployed in the California wind corridors, mostly in densely packed arrays that were not aesthetically pleasing in such a rural setting. These densely packed arrays also often blocked the wind from neighboring turbines, producing a great deal of turbulence for the downwind machines. Reliability and availability suffered as a result.

Recognizing these issues, wind operators and manufacturers have worked to develop better machines with each new generation of designs. Drag-based devices and simple lift-based designs gave way to experimentally designed and tested high-lift rotors, many with full-span pitch control. Blades that had once been made of sail or sheet metal progressed through wood to advanced fiberglass composites. The direct current (DC) alternator gave way to the grid-synchronized induction generator, which has now been replaced by variable-speed designs employing high-speed solid-state switches of advanced power electronics. Designs moved from mechanical cams and linkages that feathered or furled a machine to high-speed digital controls. A 50 kW machine, considered large in 1980, is now dwarfed by the 1.5 MW to 2.5 MW machines being routinely installed today.

Many RD&D advances have contributed to these changes. Airfoils, which are now tested in wind tunnels, are designed for insensitivity to surface roughness and dirt. Increased understanding of aeroelastic loads and the ability to incorporate this knowledge into finite element models and structural dynamics codes make the machines of today more robust but also more flexible and lighter on a relative basis than those of a decade ago.

As with any maturing technology, however, many of the simpler and easier improvements have already been incorporated into today's turbines. Increased

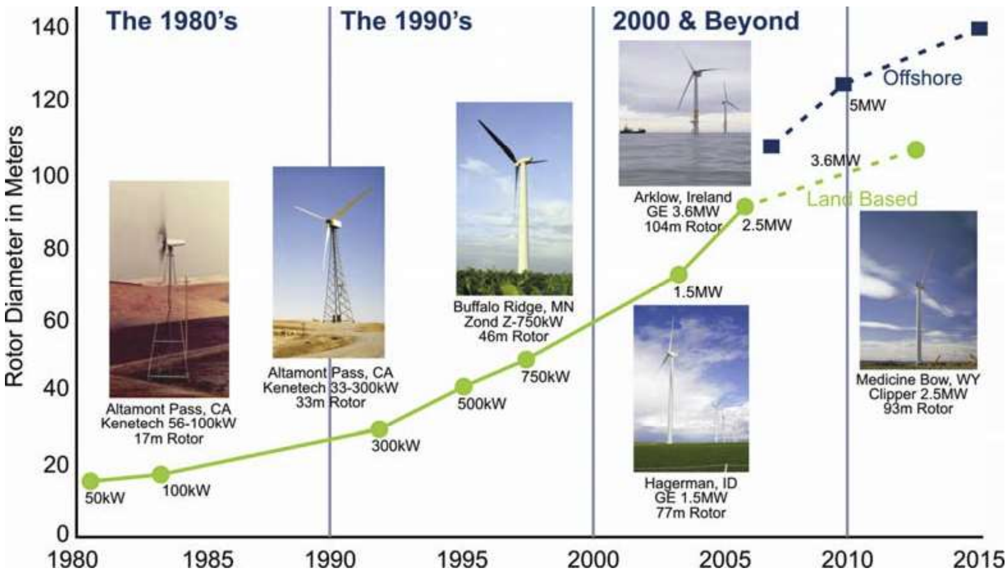
RD&D efforts and innovation will be required to continue to expand the wind energy industry.

2.2.5 Current Turbine Size

Q9

Throughout the past 20 years, average wind turbine ratings have grown almost linearly, as illustrated by Figure 2-6. Each group of wind turbine designers has predicted that its latest machine is the largest that a wind turbine will ever be. But with each new generation of wind turbines (roughly every five years), the size has grown along the linear curve and has achieved reductions in life-cycle cost of energy (COE).

Figure 2-6. The development path and growth of wind turbines

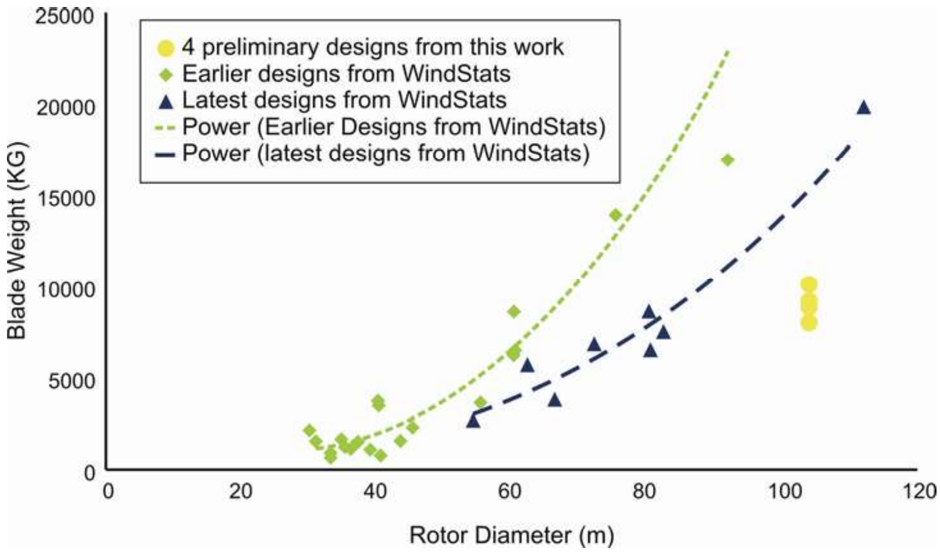


As discussed in Section 2.2.2, this long-term drive to develop larger turbines is a direct result of the desire to improve energy capture by accessing the stronger winds at higher elevations. (The increase in wind speed with elevation is referred to as wind shear.) Although the increase in turbine height is a major reason for the increase in capacity factor over time, there are economic and logistical constraints to this continued growth to larger sizes.

The primary argument for limiting the size of wind turbines is based on the square-cube law. This law roughly states that as a wind turbine rotor grows in size, its energy output increases as the rotor swept area (the diameter squared), while the volume of material, and therefore its mass and cost, increases as the cube of the diameter. In other words, at some size, the cost for a larger turbine will grow faster than the resulting energy output revenue, making scaling a losing economic game.

Engineers have successfully skirted this law by either removing material or using it more efficiently as they increase size. Turbine performance has clearly improved, and cost per unit of output has been reduced, as illustrated in Figures 2-4 and 2-5. A Wind Partnerships for Advanced Component Technology (WindPACT) study has also shown that in recent years, blade mass has been scaling at an exponent of about 2.3 as opposed to the expected 3.0 (Ashwill 2004), demonstrating how successive

Figure 2-7. Growth in blade weight



generations of blade design have moved off the cubic weight growth curve to keep weight down (see Figure 2-7). The latest designs continue to fall below the cubic line of the previous generation, indicating the continued infusion of new technology into blade design. If advanced RD&D were to result in even better design methods, as well as new materials and manufacturing methods that allow the entire turbine to scale as the diameter squared, continuing to innovate around this size limit would be possible.

Land transportation constraints can also limit wind turbine growth for turbines installed on land. Cost-effective road transportation is achieved by remaining within standard over-the-road trailer dimensions of 4.1 m high by 2.6 m wide and a gross vehicle weight (GVW) under 80,000 pounds (lb.; which translates to a cargo weight of about 42,000 lb.). Loads that exceed 4.83 m in height trigger expensive rerouting (to avoid obstructions) and often require utility and law enforcement assistance along the roadways. These dimension limits have the most impact on the base diameter of wind turbine towers. Rail transportation is even more dimensionally limited by tunnel and overpass widths and heights. Overall widths should remain within 3.4 m, and heights are limited to 4.0 m. Transportation weights are less of an issue in rail transportation, with GVW limits of up to 360,000 lb. (Ashwill 2004).

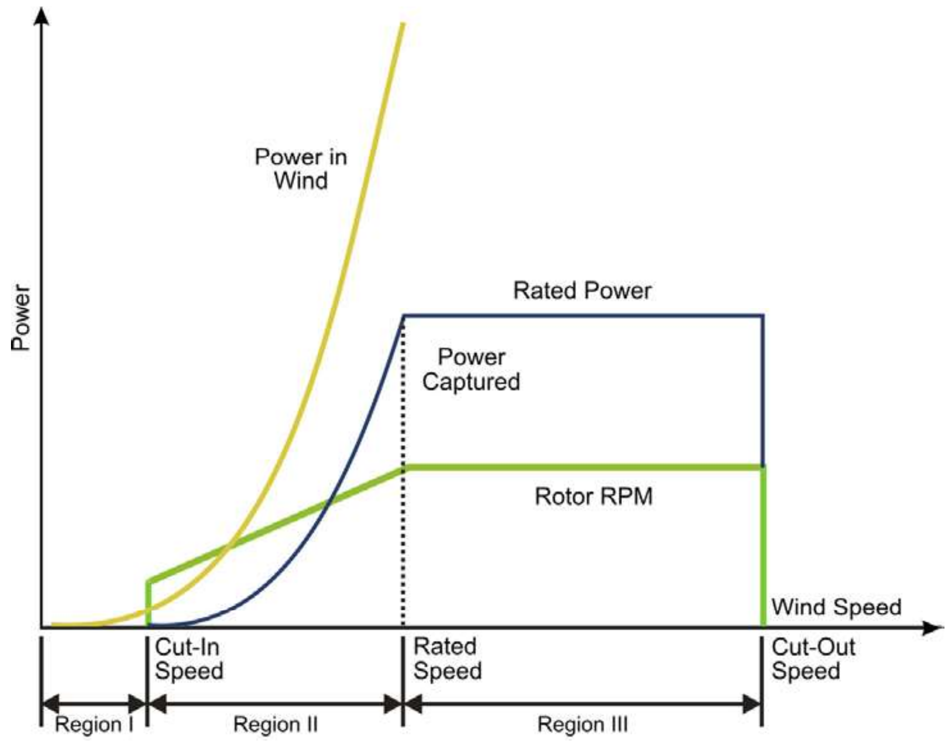
Once turbines arrive at their destination, their physical installation poses other practical constraints that limit their size. Typically, 1.5 MW turbines are installed on 80-m towers to maximize energy capture. Crane requirements are quite stringent because of the large nacelle mass in combination with the height of the lift and the required boom extension. As the height of the lift to install the rotor and nacelle on the tower increases, the number of available cranes with the capability to make this lift is fairly limited. In addition, cranes with large lifting capacities are difficult to transport and require large crews, leading to high operation, mobilization, and demobilization costs. Operating large cranes in rough or complex, hilly terrain can also require repeated disassembly to travel between turbine sites (NREL 2002).

2.2.6 Current Status of Turbine Components

The Rotor

Typically, a modern turbine will cut in and begin to produce power at a wind speed of about 5 m/s (see Figure 2-8). It will reach its rated power at about 12 m/s to 14

Figure 2-8. Typical power output versus wind speed curve



Q10

m/s, where the pitch control system begins to limit power output and prevent generator and drivetrain overload. At around 22 m/s to 25 m/s, the control system pitches the blades to stop rotation, feathering the blades to prevent overloads and damage to the turbine's components. The job of the rotor is to operate at the absolute highest efficiency possible between cut-in and rated wind speeds, to hold the power transmitted to the drivetrain at the rated power when the winds go higher, and to stop the machine in extreme winds. Modern utility-scale wind turbines generally extract about 50% of the energy in this stream below the rated wind speed, compared to the maximum energy that a device can theoretically extract, which is 59% of the energy stream (see "The Betz Limit" sidebar).

Most of the rotors on today's large-scale machines have an individual mechanism for pitch control; that is, the mechanism rotates the blade around its long axis to control the power in high winds. This device is a significant improvement over the first generation of fixed-pitch or collective-pitch linkages, because the blades can now be rotated in high winds to feather them out of the wind. This reduces the maximum loads on the system when the machine is parked. Pitching the blades out of high winds also reduces operating loads, and the combination of pitchable blades with a variable-speed generator allows the turbine to maintain generation at a constant rated-power output. The older generation of constant-speed rotors sometimes had instantaneous

The Betz Limit

Not all of the energy present in a stream of moving air can be extracted; some air must remain in motion after extraction. Otherwise, no new, more energetic air can enter the device. Building a wall would stop the air at the wall, but the free stream of energetic air would just flow around the wall. On the other end of the spectrum, a device that does not slow the air is not extracting any energy, either. The maximum energy that can be extracted from a fluid stream by a device with the same working area as the stream cross section is 59% of the energy in the stream. Because it was first derived by wind turbine pioneer Albert Betz, this maximum is known as the Betz Limit.

power spikes up to twice the rated power. Additionally, this pitch system operates as the primary safety system because any one of the three independent actuators is capable of stopping the machine in an emergency.

Blades

As wind turbines grow in size, so do their blades—from about 8 m long in 1980 to more than 40 m for many land-based commercial systems and more than 60 m for offshore applications today. Rigorous evaluation using the latest computer analysis tools has improved blade designs, enabling weight growth to be kept to a much lower rate than simple geometric scaling (see Figure 2-7). Designers are also starting to work with lighter and stronger carbon fiber in highly stressed locations to stiffen blades and improve fatigue resistance while reducing weight. (Carbon fiber, however, costs about 10 times as much as fiberglass.) Using lighter blades reduces the load-carrying requirements for the entire supporting structure and saves total costs far beyond the material savings of the blades alone.

By designing custom airfoils for wind turbines, developers have improved blades over the past 20 years. Although these airfoils were primarily developed to help optimize low-speed wind aerodynamics to maximize energy production while limiting loads, they also help prevent sensitivity to blade fouling that is caused by dirt and bug accumulation on the leading edge. This sensitivity reduction greatly improves blade efficiency (Cohen et al. 2008).

Current turbine blade designs are also being customized for specific wind classes. In lower energy sites, the winds are lighter, so design loads can be relaxed and longer blades can be used to harvest more energy in lower winds. Even though blade design methods have improved significantly, there is still much room for improvement, particularly in the area of dynamic load control and cost reduction.

Controls

Today's controllers integrate signals from dozens of sensors to control rotor speed, blade pitch angle, generator torque, and power conversion voltage and phase. The controller is also responsible for critical safety decisions, such as shutting down the turbine when extreme conditions are encountered. Most turbines currently operate in variable-speed mode, and the control system regulates the rotor speed to obtain peak efficiency in fluctuating winds. It does this by continuously updating the rotor speed and generator loading to maximize power and reduce drivetrain transient torque loads. Operating in variable-speed mode requires the use of power converters, which offer additional benefits (which are discussed in the next subsection). Research into the use of advanced control methods to reduce turbulence-induced loads and increase energy capture is an active area of work.

Electrical controls with power electronics enable machines to deliver fault-ride-through control, voltage control, and volt-ampere-reactive (VAR) support to the grid. In the early days of grid-connected wind generators, the grid rules required that wind turbines go offline when any grid event was in progress. Now, with penetration of wind energy approaching 10% in some regions of the United States, more than 8% nationally in Germany, and more than 20% of the average generation in Denmark, the rules are being changed (Wiser and Bolinger 2007). Grid rules on both continents are requiring more support and fault-ride-through protection from the wind generation component. Current electrical control systems are filling this need with wind plants carefully engineered for local grid conditions

Q11

2

The Drivetrain (Gearbox, Generator, and Power Converter)

Generating electricity from the wind places an unusual set of requirements on electrical systems. Most applications for electrical drives are aimed at using electricity to produce torque, instead of using torque to produce electricity. The applications that generate electricity from torque usually operate at a constant rated power. Wind turbines, on the other hand, must generate at all power levels and spend a substantial amount of time at low power levels. Unlike most electrical machines, wind generators must operate at the highest possible aerodynamic and electrical efficiencies in the low-power/low-wind region to squeeze every kilowatt-hour out of the available energy. For wind systems, it is simply not critical for the generation system to be efficient in above-rated winds in which the rotor is letting energy flow through to keep the power down to the rated level. Therefore, wind systems can afford inefficiencies at high power, but they require maximum efficiency at low power—just the opposite of almost all other electrical applications in existence.

Torque has historically been converted to electrical power by using a speed-increasing gearbox and an induction generator. Many current megawatt-scale turbines use a three-stage gearbox consisting of varying arrangements of planetary gears and parallel shafts. Generators are either squirrel-cage induction or wound-rotor induction, with some newer machines using the doubly fed induction design for variable speed, in which the rotor's variable frequency electrical output is fed into the collection system through a solid-state power converter. Full power conversion and synchronous machines are drawing interest because of their fault-ride-through and other grid support capacities.

As a result of fleet-wide gearbox maintenance issues and related failures with some designs in the past, it has become standard practice to perform extensive dynamometer testing of new gearbox configurations to prove durability and reliability before they are introduced into serial production. The long-term reliability of the current generation of megawatt-scale drivetrains has not yet been fully verified with long-term, real-world operating experience. There is a broad consensus that wind turbine drivetrain technology will evolve significantly in the next several years to reduce weight and cost and improve reliability.

The Tower

The tower configuration used almost exclusively in turbines today is a steel monopole on a concrete foundation that is custom designed for the local site conditions. The major tower variable is height. Depending on the wind characteristics at the site, the tower height is selected to optimize energy capture with respect to the cost of the tower. Generally, a turbine will be placed on a 60-m to 80-m tower, but 100-m towers are being used more frequently. Efforts to develop advanced tower configurations that are less costly and more easily transported and installed are ongoing.

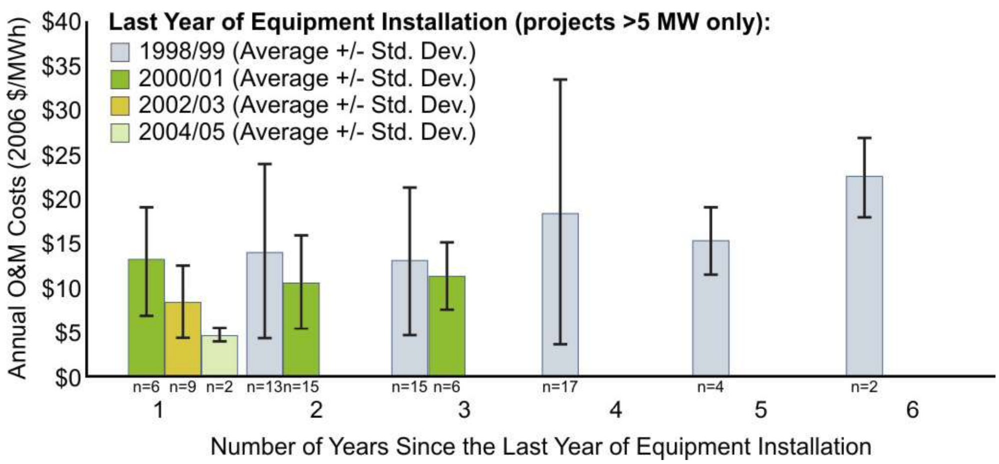
Balance of Station

The balance of the wind farm station consists of turbine foundations, the electrical collection system, power-conditioning equipment, supervisory control and data acquisition (SCADA) systems, access and service roads, maintenance buildings, service equipment, and engineering permits. Balance-of-station components contribute about 20% to the installed cost of a wind plant.

Operations and Availability

Operation and maintenance (O&M) costs have also dropped significantly since the 1980s as a result of improved designs and increased quality. O&M data from the technology installed well before 2000 show relatively high annual costs that increase with the age of the equipment. Annual O&M costs are reported to be as high as $30-$50/MWh for wind power plants with 1980s technology, whereas the latest generation of turbines has reported annual O&M costs below $10/MWh (Wiser and Bolinger 2007). Figure 2-9 shows annual O&M expenses by wind project age and equipment installation year. Relative to wind power prices shown in Figure 2-5, the O&M costs can be a significant portion of the price paid for wind-generated electricity. Since the late 1990s, modern equipment operation costs have been reduced for the initial operating years. Whether annual operation costs grow as these modern turbines age is yet to be determined and will depend greatly on the quality of these new machines.

Figure 2-9. Operation and maintenance costs for large-scale wind plants installed within the last 10 years for the early years of operation (Wiser and Bolinger 2007)



SCADA systems are being used to monitor very large wind farms and dispatch maintenance personnel rapidly and efficiently. This is one area where experience in managing large numbers of very large machines has paid off. Availability, defined as the fraction of time during which the equipment is ready to operate, is now more than 95% and often reported to exceed 98%. These data indicate the potential for improving reliability and reducing maintenance costs (Walford 2006).

2.3 TECHNOLOGY IMPROVEMENTS ON THE HORIZON

Technology improvements can help meet the cost and performance challenges embedded in this 20% Wind Scenario. The required technological improvements are relatively straightforward: taller towers, larger rotors, and continuing progress through the design and manufacturing learning curve. No single component or design innovation can fulfill the need for technology improvement. By combining a number of specific technological innovations, however, the industry can introduce new advanced architectures necessary for success. The 20% Wind Scenario does not require success in all areas; progress can be made even if only some of the technology innovations are achieved.

2.3.1 FUTURE IMPROVEMENTS TO TURBINE COMPONENTS

Many necessary technological advances are already in the active development stages. Substantial research progress has been documented, and individual companies are beginning the development process for these technologies. The risk of introducing new technology at the same time that manufacturing production is scaling up and accelerating to unprecedented levels is not trivial. Innovation always carries risk. Before turbine manufacturers can stake the next product on a new feature, the performance of that innovation needs to be firmly established and the durability needs to be characterized as well as possible. These risks are mitigated by RD&D investment, including extensive component and prototype testing before deployment.

The following are brief summaries of key wind energy technologies that are expected to increase productivity through better efficiency, enhanced energy capture, and improved reliability.

The Rotor

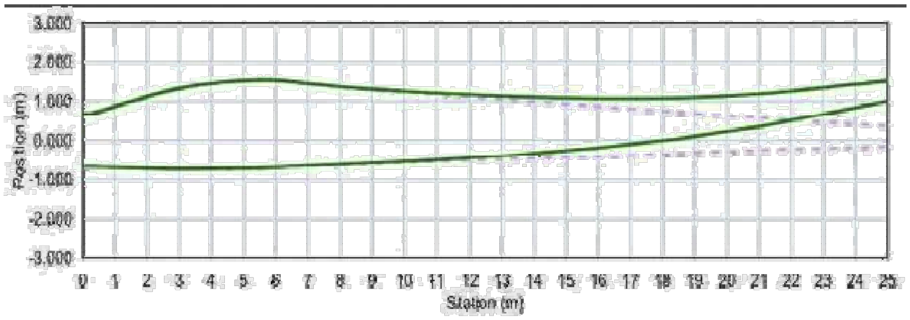
The number one target for advancement is the means by which the energy is initially captured—the rotor. No indicators currently suggest that rotor design novelties are on their way, but there are considerable incentives to use better materials and innovative controls to build enlarged rotors that sweep a greater area for the same or lower loads. Two approaches are being developed and tested to either reduce load levels or create load-resistant designs. The first approach is to use the blades themselves to attenuate both gravity- and turbulence-driven loads (see the following subsection). The second approach lies in an active control that senses rotor loads and actively suppresses the loads transferred from the rotor to the rest of the turbine structure. These improvements will allow the rotor to grow larger and capture more energy without changing the balance of the system. They will also improve energy capture for a given capacity, thereby increasing the capacity factor (Ashwill 2004).

Another innovation already being evaluated at a smaller scale by Energy Unlimited Inc. (EUI; Boise, Idaho) is a variable-diameter rotor that could significantly increase capacity factor. Such a rotor has a large area to capture more energy in low winds and a system to reduce the size of the rotor to protect the system in high winds. Although this is still considered a very high-risk option because of the difficulty of building such a blade without excessive weight, it does provide a completely different path to a very high capacity factor (EUI 2003).

Blades

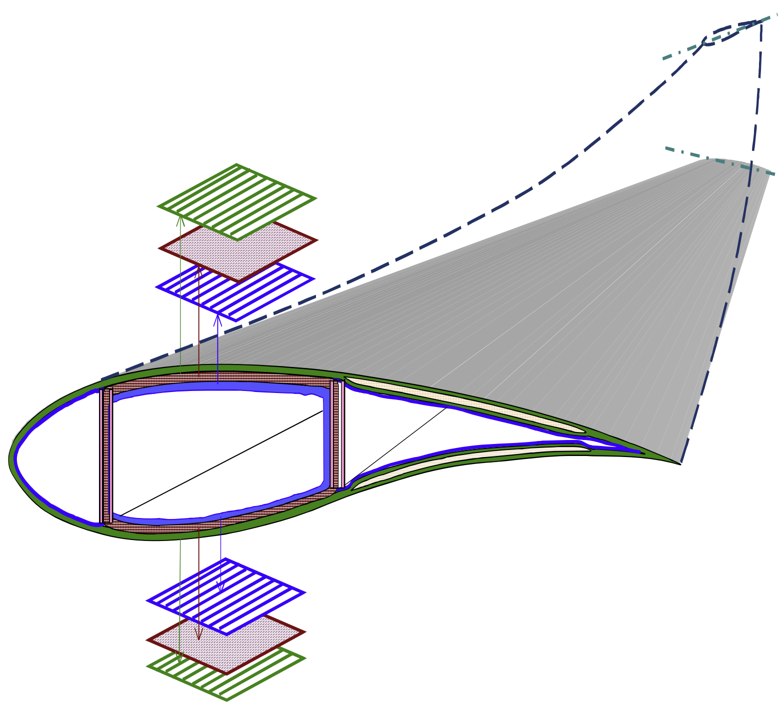
Larger rotors with longer blades sweep a greater area, increasing energy capture. Simply lengthening a blade without changing the fundamental design, however, would make the blade much heavier. In addition, the blade would incur greater structural loads because of its weight and longer moment arm. Blade weight and resultant gravity-induced loads can be controlled by using advanced materials with higher strength-to-weight ratios. Because high-performance materials such as carbon fibers are more expensive, they would be included in the design only when the payoff is maximized. These innovative airfoil shapes hold the promise of maintaining excellent power performance, but have yet to be demonstrated in full-scale operation.

Figure 2-10. Curvature-based twist coupling



One elegant concept is to build directly into the blade structure a passive means of reducing loads. By carefully tailoring the structural properties of the blade using the unique attributes of composite materials, the internal structure of the blade can be built in a way that allows the outer portion of the blade to twist as it bends (Griffin 2001). “Flap-pitch” or “bend-twist” coupling, illustrated in Figure 2-10, is accomplished by orienting the fiberglass and carbon plies within the composite layers of the blade. If properly designed, the resulting twisting changes the angle of attack over much of the blade, reducing the lift as wind gusts begin to load the blade and therefore passively reducing the fatigue loads. Yet another approach to achieving flap-pitch coupling is to build the blade in a curved shape (see Figure 2-11) so that the aerodynamic loads apply a twisting action to the blade, which varies the angle of attack as the aerodynamic loads fluctuate.

Figure 2-11. Twist-flap coupled blade design (material-based twist coupling)



To reduce transportation costs, concepts such as on-site manufacturing and segmented blades are also being explored. It might also be possible to segment molds and move them into temporary buildings close to the site of a major wind installation so that the blades can be made close to, or actually at, the wind site.

Active Controls

Q12

Active controls using independent blade pitch and generator torque can be used to reduce tower-top motion, power fluctuations, asymmetric rotor loads, and even individual blade loads. Actuators and controllers already exist that can achieve most of the promised load reductions to enable larger rotors and taller towers. In addition, some researchers have published control algorithms that could achieve the load reductions (Bossanyi 2003). Sensors capable of acting as the eyes and ears of the control system will need to have sufficient longevity to monitor a high-reliability, low-maintenance system. There is also concern that the increased control activity will accelerate wear on the pitch mechanism. Thus, the technical innovation that is essential to enabling some of the most dramatic improvements in performance is not a matter of exploring the unknown, but rather of doing the hard work of mitigating the innovation risk by demonstrating reliable application through prototype testing and demonstration.

Towers

To date, there has been little innovation in the tower, which is one of the more mundane components of a wind installation. But because placing the rotor at a higher elevation is beneficial and because the cost of steel continues to rise rapidly, it is highly likely that this component will be examined more closely in the future, especially for regions of higher than average wind shear.

Because power is related to the cube (the third power) of wind speed, mining upward into these rich veins of higher wind speed potentially has a high payoff—for example, a 10% increase in wind speed produces about a 33% increase in available power. Turbines could sit on even taller towers than those in current use if engineers can figure out how to make them with less steel. Options for using materials other than steel (e.g., carbon fiber) in the tower are being investigated. Such investigations could bear fruit if there are significant adjustments in material costs. Active controls that damp out tower motion might be another enabling technology. Some tower motion controls are already in the research pipeline. New tower erection technologies might play a role in O&M that could also help drive down the system cost of energy (COE) (NREL 2002).

Tower diameters greater than approximately 4 m would incur severe overland transportation cost penalties. Unfortunately, tower diameter and material requirements conflict directly with tower design goals—a larger diameter is beneficial because it spreads out the load and actually requires less material because its walls are thinner. On-site assembly allows for larger diameters but also increases the number of joints and fasteners, raising labor costs as well as concerns about fastener reliability and corrosion. Additionally, tower wall thickness cannot be decreased without limit; engineers must adhere to certain minima to avoid buckling. New tower wall topologies, such as corrugation, can be employed to alleviate the buckling constraint, but taller towers will inevitably cost more.

The main design impact of taller towers is not on the tower itself, but on the dynamics of a system with the bulk of its mass atop a longer, more slender structure. Reducing tower-top weight improves the dynamics of such a flexible system. The tall tower dilemma can be further mitigated with smarter controls that attenuate tower motion by using blade pitch and generator torque control. Although both approaches have been demonstrated, they are still rarely seen in commercial applications.

The Drivetrain (Gearbox, Generator, and Power Conversion)

Parasitic losses in generator windings, power electronics, gears and bearings, and other electrical devices are individually quite small. When summed over the entire system, however, these losses add up to significant numbers. Improvements that remove or reduce the fixed losses during low power generation are likely to have an important impact on raising the capacity factor and reducing cost. These improvements could include innovative power-electronic architectures and large-scale use of permanent-magnet generators. Direct-drive systems also meet this goal by eliminating gear losses. Modular (transportable) versions of these large generation systems that are easier to maintain will go a long way toward increasing the productivity of the low-wind portion of the power curve.

Currently, gearbox reliability is a major issue, and gearbox replacement is quite expensive. One solution is a direct-drive power train that entirely eliminates the gearbox. This approach, which was successfully adopted in the 1990s by Enercon-GmbH (Aurich, Germany), is being examined by other turbine manufacturers. A less radical alternative reduces the number of stages in the gearbox from three to two or even one, which enhances reliability by reducing the parts count. The fundamental gearbox topology can also be improved, as Clipper Windpower (Carpinteria, California) did with its highly innovative multiple-drive-path gearbox, which divides mechanical power among four generators (see Figure 2-12). The multiple-drive-path design radically decreases individual gearbox component loads, which reduces gearbox weight and size, eases erection and maintenance demands, and improves reliability by employing inherent redundancies.

The use of rare-earth permanent magnets in generator rotors instead of wound rotors also has several advantages. High energy density eliminates much of the weight associated with copper windings, eliminates problems associated with insulation degradation and shorting, and reduces electrical losses. Rare-earth magnets cannot be subjected to elevated temperatures, however, without permanently degrading magnetic field strength, which imposes corresponding demands on generator cooling reliability. The availability of rare-earth permanent magnets is a potential concern because key raw materials are not available in significant quantities within the United States (see Chapter 3).

Power electronics have already achieved elevated performance and reliability levels, but opportunities for significant improvement remain. New silicon carbide (SiC) devices entering the market could allow operation at higher temperature and higher frequency, while improving reliability, lowering cost, or both. New circuit topologies could furnish better control of power quality, enable higher voltages to be used, and increase overall converter efficiency.

Distributed Energy Systems (Wallingford, Connecticut; formerly Northern Power Systems) has built an advanced prototype power electronics system that will deliver lower losses and conversion costs for permanent-magnet generators (Northern Power Systems 2006). Peregrine Power (Wilsonville, Oregon) has concluded that using SiC devices would reduce power losses, improve reliability, and shrink components by orders of magnitude (Peregrine Power 2006). A study completed by BEW Engineering (San Ramon, California; Behnke, Erdman, and Whitaker Engineering 2006) shows that using medium-voltage power systems for multimegawatt turbines could reduce the cost, weight, and volume of turbine electrical components as well as reduce electrical losses.

Figure 2-12. Clipper Windpower multiple-drive-path gearbox

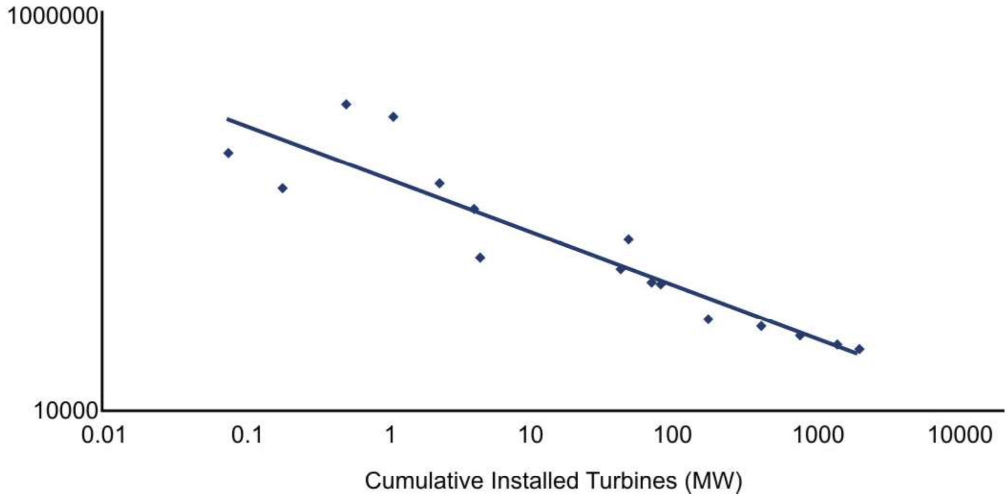
The most dramatic change in the long-term application of wind generation may come from the grid support provided by the wind plant. Future plants will not only support the grid by delivering fault-ride-through capability as well as frequency, voltage, and VAR control, but will also carry a share of power control capability for the grid. Plants can be designed so that they furnish a measure of dispatch capability, carrying out some of the traditional duties of conventional power plants. These plants would be operated below their maximum power rating most of the time and would trade some energy capture for grid ancillary services. Paying for this trade-off will require either a lower capital cost for the hardware, contractual arrangements that will pay for grid services at a high enough rate to offset the energy loss, or optimally, a combination of the two. Wind plants might transition, then, from a simple energy source to a power plant that delivers significant grid support.

2.3.2 Learning-Curve Effect

Progressing along the design and manufacturing learning curve allows engineers to develop technology improvements (such as those listed in Section 2.3.1) and reduce capital costs. The more engineers and manufacturers learn by conducting effective RD&D and producing greater volumes of wind energy equipment, the more proficient and efficient the industry becomes. The learning curve is often measured by calculating the progress ratio, defined as the ratio of the cost after doubling cumulative production to the cost before doubling.

The progress ratio for wind energy from 1984 to 2000 was calculated for the high volume of machines installed in several European countries that experienced a healthy combination of steadily growing manufacturing output, external factors, and research investment during that time. Results show that progress ratio estimates were approximately the same for Denmark (91%), Germany (94%), and Spain (91%) (ISET 2003). At the time this report was written, there was not enough reliable data on U.S.-based manufacturing of wind turbines to determine a U.S. progress ratio. Figure 2-13 shows the data for Spain.

Figure 2-13. Cost of wind turbines delivered from Spain between 1984 and 2000



Note: The Y axis represents cost and is presented in logarithmic units. The data points shown fit the downward-sloping straight line with a correlation coefficient, r^2, of 0.85.

Moving from the current level of installed wind capacity of roughly 12 gigawatts (GW) to the 20% Wind Scenario total of 305 GW will require between four and five doublings of capacity. If the progress ratio of 91% shown in Figure 2-13 continues, prices could drop to about 65% of current costs, a 35% reduction. The low-hanging fruit of cost reduction, however, has already been harvested. The industry has progressed from machines based on designs created without any design tools and built almost entirely by hand to the current state of advanced engineering capability. The assumption in the 20% Wind Scenario is that a 10% reduction in capital cost could accelerate large-scale deployment. In order to achieve this reduction, a progress ratio of only 97.8% is required to produce a learning curve effect of 10% with 4.6 doublings of capacity. With sustained manufacturing growth and technological advancement, there is no technical barrier to achieving 10% capital cost reduction. See Appendix B for further discussion.

2.3.3 The System Benefits of Advanced Technology

A cost study conducted by the U.S. Department of Energy (DOE) Wind Program identified numerous opportunities for technology advancement to reduce the life-cycle COE (Cohen and Schweizer et al. 2008). Based on machine performance and cost, this study used advanced concepts to suggest pathways that integrate the individual contributions from component-level improvements into system-level estimates of the capital cost, annual energy production, reliability, O&M, and balance of station. The results, summarized in Table 2-1, indicate significant potential impacts on annual energy production and capital cost. Changes in annual energy production are equivalent to changes in capacity factor because the turbine rating was fixed. A range of values represents the best, most likely, and least beneficial outcomes.

The Table 2-1 capacity factor improvement of 11% that results from taller towers reflects the increase in wind resources at a hub height of 120 m, conservatively assuming the standard wind shear distribution meteorologists use for open country. Uncertainty in these capacity factor improvements are reflected in the table below. Depending on the success of new tower technology, the added costs could range from 8% to 20%, but there will definitely be an added cost if the tower is the only component in the system that is modified to take the rotor to higher elevations. An advantage would come from a system design in which the tower head mass is significantly reduced with the integration of a rotor and drivetrain that are significantly lighter.

Q13

Table 2-1. Areas of potential technology improvement

Technical Area	Potential Advances	Performance and Cost Increments (Best/Expected/Least Percentages)	
		Annual Energy Production	Turbine Capital Cost
Advanced Tower Concepts	• Taller towers in difficult locations • New materials and/or processes • Advanced structures/foundations • Self-erecting, initial, or for service	+11/+11/+11	+8/+12/+20
Advanced (Enlarged) Rotors	• Advanced materials • Improved structural-aero design • Active controls • Passive controls • Higher tip speed/lower acoustics	+35/+25/+10	-6/-3/+3
Reduced Energy Losses and Improved Availability	• Reduced blade soiling losses • Damage-tolerant sensors • Robust control systems • Prognostic maintenance	+7/+5/0	0/0/0
Drivetrain (Gearboxes and Generators and Power Electronics)	• Fewer gear stages or direct-drive • Medium/low speed generators • Distributed gearbox topologies • Permanent-magnet generators • Medium-voltage equipment • Advanced gear tooth profiles • New circuit topologies • New semiconductor devices • New materials (gallium arsenide [GaAs], SiC)	+8/+4/0	-11/-6/+1
Manufacturing and Learning Curve*	• Sustained, incremental design and process improvements • Large-scale manufacturing • Reduced design loads	0/0/0	-27/-13/-3
Totals		+61/+45/+21	-36/-10/+21

*The learning curve results from the NREL report (Cohen and Schweizer et al. 2008) are adjusted from 3.0 doublings in the reference to the 4.6 doublings in the 20% Wind Scenario.

The capital cost reduction shown for the drivetrain components is mainly attributed to the reduced requirements on the structure when lighter components are placed on the tower top. Performance increases as parasitic losses in mechanical and electrical components are reduced. Such components are designed specifically to optimize the performance for wind turbine characteristics. The improvements shown in Table 2-1 are in the single digits, but are not trivial.

Without changing the location of the rotor, energy capture can also be increased by using longer blades to sweep more area. A 10% to 35% increase in capacity factor is produced by 5% to 16% longer blades for the same rated power output. Building these longer blades at an equal or lower cost is a challenge, because blade weight must be capped while turbulence-driven loads remain no greater than what the smaller rotor can handle. With the potential of new structurally efficient airfoils, new materials, passive load attenuation, and active controls, it is estimated that this magnitude of blade growth can be achieved in combination with a modest system cost reduction.

Technology advances can also reduce energy losses in the field. Improved O&M techniques and monitoring capabilities can reduce downtime for repairs and scheduled maintenance. It is also possible to mitigate losses resulting from degradation of performance caused by wear and dirt over time. These improvements are expected to be in the single digits at best, with an approximate 5% improvement in lifetime energy capture.

Doubling the number of manufactured turbines several times over the years will produce a manufacturing learning-curve effect that can also help reduce costs. The learning-curve effects shown in Table 2-1 are limited to manufacturing-related technology improvements and do not reflect issues of component selection and design. As discussed in Section 2.3.2, the learning curve reflects efficiencies driven by volume production and manufacturing experience as well as the infusion of manufacturing technology and practices that encourage more manufacturing-friendly design in the future. Although these changes do not target any added energy capture, they are expected to result in continuous cost reductions. The only adjustment from the NREL reference (Cohen and Schweizer et al. 2008) is that the 20% Wind Scenario by 2030 requires 4.6 doublings of cumulative capacity rather than the 3.0 doublings used in the reference targeted at the year 2012. The most likely 13% cost reduction assumes a conservative progress ratio of 97% per doubling of capacity. However, there are a range of possible outcomes.

The potential technological advances outlined here support the technical feasibility of the 20% Wind Scenario by outlining several possible pathways to a substantial increase in capacity factor accompanied by a modest but double-digit reduction in capital cost.

2.3.4 Targeted RD&D

While there is an expected value to potential technology improvements, the risk of implementing them has not yet been reduced to the level that allows those improvements to be used in commercial hardware. The issues are well known and offer an opportunity for focused RD&D efforts. In the past, government and industry collaboration has been successful in moving high-risk, high-potential technologies into the marketplace.

One example of such collaboration is the advanced natural gas turbine, which improved the industry efficiency standard—which had been capped at 50%—to almost 60%. DOE invested $100 million in the H-system turbine and General Electric (GE) invested $500 million. Although it was known that higher operating temperatures would lead to higher efficiency, there were no materials for the turbine blades that could withstand the environment. The research program focused on advanced cooling techniques and new alloys to handle combustion that was nearly 300°F hotter. The project produced the world's largest single crystal turbine blades capable of resisting high-temperature cracking. The resulting "H system" gas turbine is 11.89 m long, 4.89 m in diameter, and weighs more than 811,000 lb. Each turbine is expected to save more than $200 million in operating costs over its lifetime (DOE 2000).

A similar example comes from the aviation world. The use of composite materials was known to provide excellent benefits for light-jet airframes, but the certification process to characterize the materials was onerous and expensive. NASA started a program to "reduce the cost of using composites and develop standardized procedures for certifying composite materials" (Brown 2007). The Advanced General Aviation Transport Experiments (AGATE), which began in 1994, solved those problems and opened the door for new composite material technology to be applied to the light-jet application. A technology that would have been too high-risk for the individual companies to develop was bridged into the marketplace through a cooperative RD&D effort by NASA, the Federal Aviation Administration (FAA), industry, and universities. The Adam aircraft A500 turboprop and the A700 very light jet are examples of new products based on this composite technology.

Some might claim that wind technology is a finished product that no longer needs additional RD&D, or that all possible improvements have already been made. The reality is that the technology is substantially less developed than fossil energy technology, which is still being improved after a century of generating electricity. A GE manager who spent a career in the gas turbine business and then transferred to manage the wind turbine business noted the complexity of wind energy technology: "Our respect for wind turbine technology has grown tremendously. The practical side is so complex and forces are so dramatic. We would never have imagined how complex turbines are" (Knight and Harrison 2005).

Already, there is a clear understanding of the materials, controls, and aerodynamics issues that must be resolved to make progress toward greater capacity factors. The combination of reduced capital cost and increased capacity factor will lead to reduced COE. Industry feels the risk of bringing new technology into the marketplace without a full-scale development program is too great and believes sustained RD&D would help reduce risk and help enable the transfer of new technology to the marketplace.

2.4 Addressing Technical and Financial Risks

Risks tend to lessen industry's desire to invest in wind technology. The wind plant performance track record, in terms of generated revenues and operating costs compared with the estimated revenues used in plant financing, will drive the risk level of future installations. The consequences of these risks directly affect the revenues of owners of wind manufacturing and operating capabilities.

2.4.1 Direct Impacts

When owners of wind manufacturing and operating capabilities directly bear the costs of failure, the impacts are said to be direct. This direct impact on revenue is often caused by:

- **Increasing O&M costs:** As discussed previously and illustrated in Figure 2-9, there is mounting evidence that O&M costs are increasing as wind farms age. Most of these costs are associated with unplanned maintenance or components wearing out before the end of their intended design lives. Some failures can be traced to poor manufacturing or installation quality. Others are caused by design errors, many of which are caused by weaknesses in the technology's state of the art, generally codified by the design process. Figures 2-14 and 2-15 both show steadily rising O&M costs for wind farms installed in the United States in the two decades before the turn of the century, and Figure 2-14 shows the components that have caused these increasing costs. The numbers and costs of component failures increase with time, and the risk to the operators grows accordingly. In Figure 2-14, the solid lines represent expected repairs that may not be completely avoidable, and the dashed lines show potential early failures that can significantly increase risk.
- **Poor availability driven by low reliability:** Energy is not generated while components are being repaired or replaced. Although a single failure of a critical component stops production from only one turbine, such losses can mount up to significant sums of lost revenue.
- **Poor wind plant array efficiency:** If turbines are placed too close together, their wakes interact, which can cause the downwind turbines to perform poorly. But if they are placed too far apart, land and plant maintenance costs increase.

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Figure 2-14. Unplanned repair cost, likely sources, and risk of failure with wind plant age

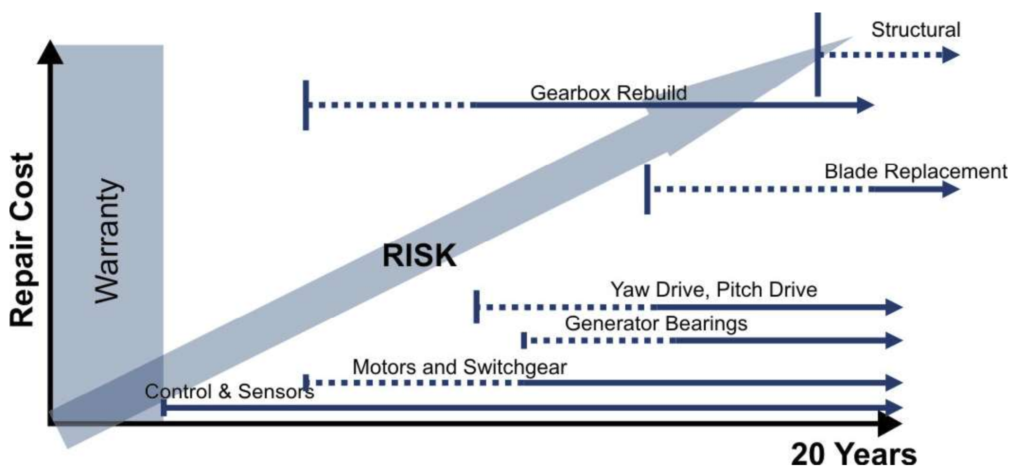
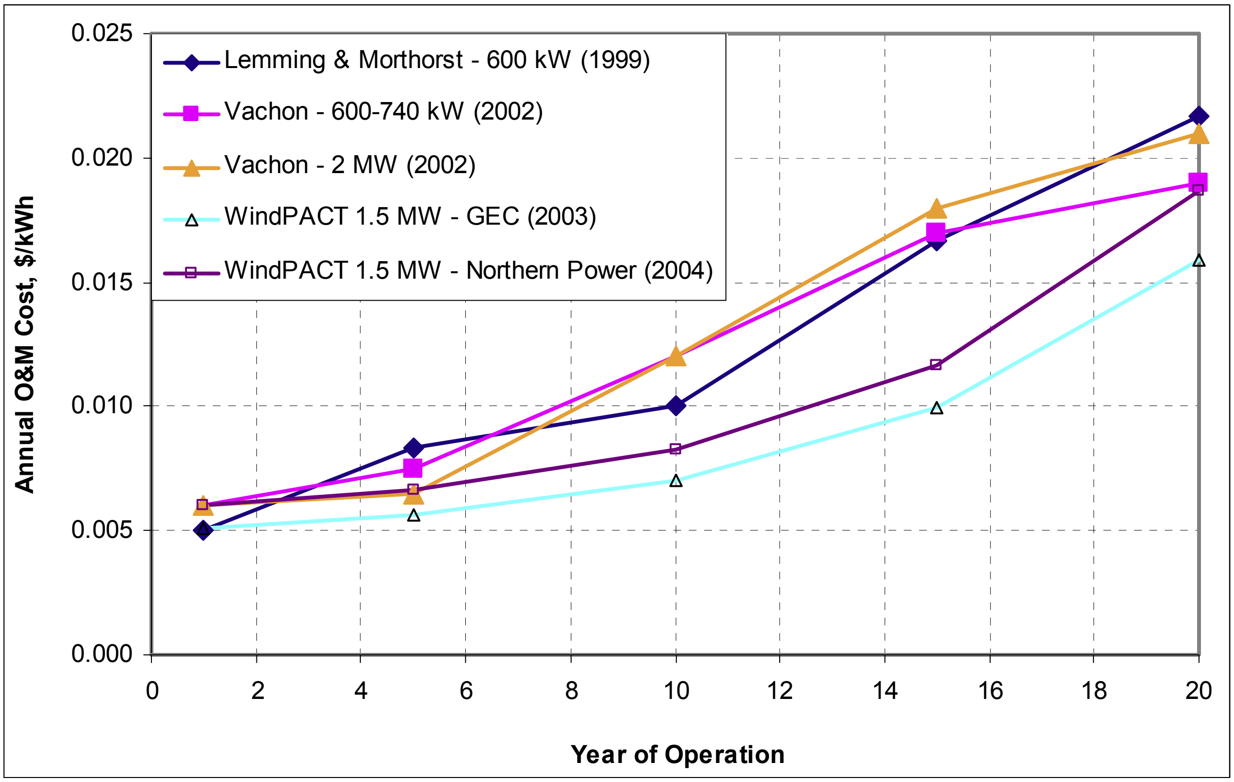


Figure 2-15. Average O&M costs of wind farms in the United States



2.4.2 Indirect Impacts

Although the wind industry has achieved high levels of wind plant availability and reliability, unpredictable or unreliable performance would threaten the credibility of this emerging technology in the eyes of financial institutions. The consequences of real or perceived reliability problems would extend beyond the direct cost to the plant owners. These consequences on the continued growth of investment in wind could include:

- **Increased cost of insurance and financing:** Low interest rates and long-term loans are critical to financing power plants that are loaded with upfront capital costs. Each financial institution will assess the risk of investing in wind energy and charge according to those risks. If wind power loses credibility, these insurance and financing costs could increase.
- **Slowing or stopping development:** Lost confidence contributed to the halt of development in the United States in the late 1980s through the early 1990s. Development did not start again until the robust European market supported the technology improvements necessary to reestablish confidence in reliable European turbines. As a result, the current industry is dominated by European wind turbine companies. Active technical supporters of RD&D must anticipate and resolve problems before they threaten industry development.
- **Loss of public support:** If wind power installations do not operate continuously and reliably, the public might be easily convinced that

renewable energy is not a viable source of energy. The public's confidence in the technology is crucial. Without public support, partnerships working toward a new wind industry future cannot be successful.

2.4.3 Risk Mitigation Through Certification, Validation, and Performance Monitoring

To reduce risk, the wind industry requires turbines to adhere to international standards. These standards, which represent the collective experience of the industry's leading experts, imply a well-developed design process that relies on the most advanced design tools, testing for verification, and disciplined quality control.

Certification

Certification involves high-level, third-party technical audits of a manufacturer's design development. It includes a detailed review of design analyses, material selections, dynamic modeling, and component test results. The wind industry recognizes that analytical reviews are not sufficient to capture weaknesses in the design process. Therefore, consensus standard developers also require full-scale testing of blades, gearboxes, and the complete system prototype (see "Industry Standards" sidebar).

> **Industry Standards**
>
> The American National Standards Institute (ANSI) has designated the American Wind Energy Association (AWEA) as the lead organization for the development and publication of industry consensus standards for wind energy equipment and services in the United States. AWEA also participates in the development of international wind energy standards through its representation on the International Electrotechnical Commission (IEC) TC-88 Subcommittee. Information on these standards can be accessed on AWEA's Web site (http://www.awea.org/standards).

Actively complying with these standards encourages investment in wind energy by ensuring that turbines reliably achieve the maximum energy extraction needed to expand the industry.

Full-Scale Testing

Testing standards were drafted to ensure that accredited third-party laboratories are conducting tests consistently. These tests reveal many design and manufacturing deficiencies that are beyond detection by analytical tools. They also provide the final verification that the design process has worked and give the financial community the confidence needed to invest in a turbine model.

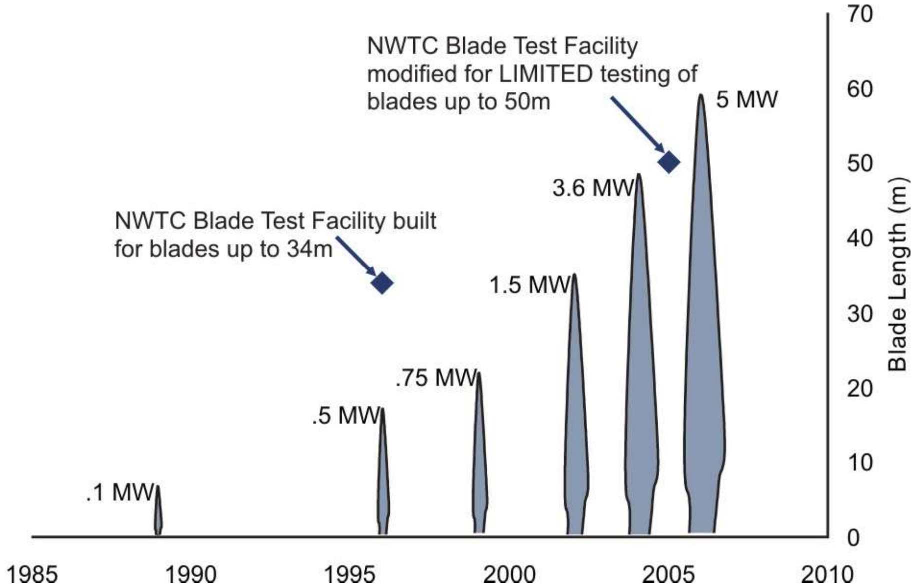
Full-scale test facilities and trained test engineers capable of conducting full-scale tests are rare. The facilities must have equipment capable of applying tremendous loads that mimic the turbulence loading that wind applies over the entire life of the blade or gearbox. Full-scale prototype tests are conducted in the field at locations with severe wind conditions. Extensive instrumentation is applied to the machine, according to a test plan prescribed by international standards, and comprehensive data are recorded over a specified range of operating conditions. These data give the certification agent a means for verifying the accuracy of the design's analytical basis. The industry and financial communities depend on these facilities and skilled test engineers to support all new turbine component development.

As turbines grow larger and more products come on the market, test facilities must also grow and become more efficient. New blades are reaching 50 m in length, and the United States has no facilities that can test blades longer than 50 m. Furthermore, domestic dynamometer facilities capable of testing gearboxes or new drivetrains are limited in capacity to 1.5 MW. The limited availability of facilities and qualified test engineers increases the deployment risk of new machines that are not subjected to the rigors of current performance validation in accredited facilities.

At full-scale facilities, it is also difficult to conduct tests accurately and capture the operating conditions that are important to verify the machine's reliability. These tests are expensive to conduct and accreditation is expensive to maintain for several reasons. First, the scale of the components is one of the largest of any commercial industry. Because blades are approaching sizes of half the length of a football field and can weigh more than a 12.2 m yacht, they are very difficult and expensive to transport on major highways. The magnitude of torque applied to the drivetrains for testing is among the largest of any piece of rotating equipment ever constructed. Figure 2-16 shows the largest blades being built and the approximate dates when U.S. blade test facilities were built to accommodate their testing.

Although it is very expensive for each manufacturer to develop and maintain

Figure 2-16. Blade growth and startup dates for U.S. blade test facilities



facilities of this scale for its own certification testing needs, without these facilities, rapid technological progress will be accompanied by high innovation risk. Wind energy history has proven that these kinds of tests are crucial for the industry's success and the financial community's confidence. These tests, then, are an essential element of any risk mitigation strategy.

Performance Monitoring and O&M

One of the main elements of power plant management is strategic monitoring of reliability. Other industries have established anonymous databases that serve to benchmark their reliability and performance, giving operators both the ability to recognize a drop in reliability and the data they need to determine the source of low reliability. The wind industry needs such a strategically designed database, which would give O&M managers the tools to recognize and pinpoint drops in reliability, along with a way to collectively resolve technical problems. Reliability databases are an integral part of more sophisticated O&M management tools. Stiesdal and Madsen (2005) describe how databases can be used for managing O&M and improving future designs.

In mature industries, O&M management tools are available to help maximize maintenance efficiency. Achieving this efficiency is a key factor in minimizing the COE and maximizing the life of wind plants, thereby increasing investor confidence. Unlike central generation facilities, wind plants require maintenance strategies that minimize human attention and maximize remote health monitoring and automated fault data diagnosis. This requires intimate knowledge of healthy plant operating characteristics and an ability to recognize the characteristics of very complex faults that might be unique to a specific wind plant. Such tools do not currently exist for the wind industry, and their development will require RD&D to study wind plant systems interacting with complex atmospheric conditions and to model the interactions. The resultant deeper understanding will allow expert systems to be developed, systems that will aid operators in their quest to maximize plant performance and minimize operating costs through risk mitigation. These systems will also produce valuable data for improving the next generation of turbine designs.

2.5 Offshore Wind Technology

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Offshore wind energy installations have a broadly dispersed, abundant resource and the economic potential for cost competitiveness that would allow them to make a large impact in meeting the future energy needs of the United States (Musial 2007). Of the contiguous 48 states, 28 have a coastal boundary. U.S. electric use data show that these same states use 78% of the nation's electricity (EIA 2006). Of these 28 states, only 6 have a sufficient land-based wind energy resource to meet more than 20% of their electric requirements through wind power. If shallow water offshore potential (less than 30 m in depth) is included in the wind resource mix, though, 26 of the 28 states would have the wind resources to meet at least 20% of their electric needs, with many states having sufficient offshore wind resources to meet 100% of their electric needs (Musial 2007). For most coastal states, offshore wind resources are the only indigenous energy source capable of making a significant energy contribution. In many congested energy-constrained regions, offshore wind plants might be necessary to supplement growing demand and dwindling fossil supplies.

Twenty-six offshore wind projects with an installed capacity of roughly 1,200 MW now operate in Europe. Most of these projects were installed in water less than 22 m deep. One demonstration project in Scotland is installed in water at a depth of 45 m. Although some projects have been hampered by construction overruns and higher-than-expected maintenance requirements, projections show strong growth in many European Union (EU) markets. For example, it is estimated that offshore wind capacity in the United Kingdom will grow by 8,000 MW by 2015. Similarly, German offshore development is expected to reach 5,600 MW by 2014 (BSH; BWEA).

In the United States, nine offshore project proposals in state and federal waters are in various stages of development. Proposed projects on the Outer Continental Shelf are under the jurisdiction of the Minerals Management Service (MMS) with their authority established by the Energy Policy Act (EPAct) of 2005 (MMS). Several states are pursuing competitive solicitations for offshore wind projects approval.

2.5.1 COST OF ENERGY

The current installed capital cost of offshore projects is estimated in the range of $2,400 to $5,000 per kW (Black & Veatch 2007; Pace Global 2007). Because offshore wind energy tends to take advantage of extensive land-based experience and mature offshore oil and gas practices, offshore cost reductions are not expected to be as great as land-based reductions spanning the past two decades. However, offshore wind technology is considerably less mature than land-based wind energy, so it does have significant potential for future cost reduction. These cost reductions are achievable through technology development and innovation, implementation and customization of offshore oil and gas practices, and learning-curve reductions that take advantage of more efficient manufacturing and deployment processes and procedures.

2.5.2 CURRENT TECHNOLOGY

Today's baseline technology for offshore wind turbines is essentially a version of the standard land-based turbine adapted to the marine environment. Although turbines of up to 5 MW have been installed, most recent orders from Vestas (Randers, Denmark) and Siemens (Munich, Germany), the two leading suppliers of offshore wind turbines, range from 2.0 MW to 3.6 MW.

The architecture of the baseline offshore turbine and drivetrain comprises a three-bladed upwind rotor, typically 90 m to 107 m in diameter. Tip speeds of offshore turbines are slightly higher than those of land-based turbines, which have speeds of 80 m/s or more. The drivetrain consists of a gearbox generally run with variable-speed torque control that can achieve generator speeds between 1,000 and 1,800 rpm. The offshore tower height is generally 80 m, which is lower than that of land-based towers, because wind shear profiles are less steep, tempering the advantage of tower height.

The offshore foundation system baseline technology uses monopiles at nominal water depths of 20 m. Monopiles are large steel tubes with a wall thickness of up to 60 mm and diameters of 6 m. The embedment depth varies with soil type, but a typical North Sea installation must be embedded 25 m to 30 m below the mud line. The monopile extends above the surface where a transition piece with a flange to fasten the tower is leveled and grouted. Its foundation requires a specific class of installation equipment for driving the pile into the seabed and lifting the turbine and tower into place. Mobilization of the infrastructure and logistical support for a large offshore wind plant accounts for a significant portion of the system cost.

Turbines in offshore applications are arranged in arrays that take advantage of the prevailing wind conditions measured at the site. Turbines are spaced to minimize aggregate power plant energy losses, interior plant turbulence, and the cost of cabling between turbines.

The power grid connects the output from each turbine, where turbine transformers step up the generator and the power electronics voltage to a distribution voltage of about 34 kilovolts (kV). The distribution system collects the power from each turbine at a central substation where the voltage is stepped up and transmitted to shore through a number of buried, high-voltage subsea cables. A shore-based interconnection point might be used to step up the voltage again before connecting to the power grid.

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Shallow water wind turbine projects have been proposed and could be followed by transitional and finally deepwater turbines. These paths should not be considered as mutually exclusive choices. Because there is a high degree of interdependence among them, they should be considered a sequence of development that builds from a shallow water foundation of experience and knowledge to the complexities of deeper water.

2.5.3 Technology Needs and Potential Improvements

Offshore, wind turbine cost represents only one-third of the total installed cost of the wind project, whereas on land, the turbine cost represents more than half of the total installed cost. To lower costs for offshore wind, the focus must be on lowering the balance-of-station costs. These costs, which include those for foundations, electrical grids, O&M, and installation and staging costs, dominate the system COE. Turbine improvements that make turbines more reliable, more maintainable, more rugged, and larger, will still be needed to achieve cost goals. Although none of these improvements are likely to lower turbine costs, the net result will lower overall system costs.

Commercialization of offshore wind energy faces many technical, regulatory, socioeconomic, and political barriers, some of which may be mitigated through targeted short- and long-range RD&D efforts. Short-term research addresses impediments that prevent initial industry projects from proceeding and helps sharpen the focus for long-term research. Long-term research involves a more complex development process resulting in improvements that can help lower offshore life-cycle system costs.

Short-Term RD&D Options

Conducting research that will lead to more rapid deployment of offshore turbines should be an upfront priority for industry. This research should address obstacles to today’s projects, and could include the following tasks:

- **Define offshore resource exclusion zones:** A geographically based exclusion study using geographic information system (GIS) land use overlays would more accurately account for all existing and future marine uses and sensitive areas. This type of exclusion study could be part of a regional programmatic environmental impact statement and is necessary for a full assessment of the offshore resource (Dhanju, Whitaker, and Kempton 2006). Currently, developers bear the burden of siting during a pre-permitting phase with very little official guidance. This activity should be a jointly funded industry project conducted on a regional basis.
- **Develop certification methods and standards:** MMS has been authorized to define the structural safety standards for offshore wind turbines on the OCS. Technical research, analysis, and testing are needed to build confidence that safety will be adequate, and to prevent overcautiousness that will increase costs unnecessarily. Developing these standards will require a complete evaluation and harmonization of the existing offshore wind standards and the American Petroleum Institute (API) offshore oil and gas standards. MMS is currently determining the most relevant standards.
- **Develop design codes, tools, and methods:** The design tools that the wind industry uses today have been developed and validated for

land-based utility-scale turbines, and the maturity and reliability of the tools have led to significantly higher confidence in today's wind turbines. By comparison, offshore design tools are relatively immature. The development of accurate offshore computer codes to predict the dynamic forces and motions acting on turbines deployed at sea is essential for moving into deeper water. One major challenge is predicting loads and the resulting dynamic responses of the wind turbine's support structure when it is subjected to combined wave and wind loading. These offshore design tools must be validated to ensure that they can deal with the combined dominance of simultaneous wind and wave load spectra, which is a unique problem for offshore wind installations. Floating system analysis must be able to account for additional turbine motions as well as the dynamic characterization of mooring lines.

- **Site turbines and configure arrays:** The configuration and spacing of wind turbines within an array have a marked effect on power production from the aggregate wind plant, as well as for each individual turbine. Uncertainties in power production represent a large economic risk factor for offshore development. Offshore wind plants can lose more than 10% of their energy to array losses, but improvements in array layout and array optimization models could deliver substantial recovery (SEAWIND 2003). Atmospheric boundary layer interaction with the turbine wakes can affect both energy capture and plant-generated turbulence. Accurate characterization of the atmospheric boundary layer behavior and more accurate wake models will be essential for designing turbines that can withstand offshore wind plant turbulence. Wind plant design tools that are able to characterize turbulence generated by wind plants under a wide range of conditions are likely necessary.
- **Develop hybrid wind-speed databases:** Wind, sea-surface temperatures, and other weather data are housed in numerous satellite databases available from the National Oceanic and Atmospheric Administration (NOAA), NASA, the National Weather Service (NWS), and other government agencies. These data can be combined to supplement the characterization of coastal and offshore wind regimes (Hasager et al. 2005). The limitations and availability of existing offshore data must be understood. Application of these data to improve the accuracy of offshore wind maps will also be important.

Long-Term R&D Options

Long-term research generally requires hardware development and capital investment, and it must take a complex development path that begins early enough for mature technology to be ready when needed. Most long-term research areas relate to lowering offshore life-cycle system costs. These areas are subdivided into infrastructure and turbine-specific needs. Infrastructure to support offshore wind development represents a major cost element. Because this is a relatively new technology path, there are major opportunities for reducing the cost impacts. Although land-based wind turbine designs can generally be used for offshore deployment, the offshore environment will impose special requirements on turbines. These requirements must be taken into account to optimize offshore deployment. Areas where industry should focus efforts include:

2

- **Minimize work at sea:** There are many opportunities to lower project costs by reallocating the balance between work done on land and at sea. The portion of labor devoted to project O&M, land-based installation and assembly, and remote inspections and diagnostics can be rebalanced with upfront capital enhancements, such as higher quality assurance, more qualification testing, and reliable designs. This rebalancing might enable a significant life-cycle cost reduction by shifting the way wind projects are designed, planned, and managed.
- **Enhance manufacturing, installation and deployment strategies:** New manufacturing processes and improvements in existing processes that reduce labor and material usage and improve part quality have high potential for reducing costs in offshore installations. Offshore wind turbines and components could be constructed and assembled in or near seaport facilities that allow easy access from the production area to the installation site, eliminating the necessity of shipping large components over inland roadways. Fabrication facilities must be strategically located for mass-production, land-based assembly, and for rapid deployment with minimal dependence on large vessels. Offshore system designs that can be floated out and installed without large cranes can reduce costs significantly. New strategies should be integrated into the turbine design process at an early stage (Lindvig 2005; Poulsen and Skjærbæk 2005).
- **Incorporate offshore service and accessibility features:** To manage O&M, predict weather windows, minimize downtime, and reduce the equipment needed for up-tower repairs, operators should be equipped with remote, intelligent, turbine condition monitoring and self-diagnostic systems. These systems can alert operators to the need for operational changes, or enable them to schedule maintenance at the most opportune times. A warning about an incipient failure can alert the operators to replace or repair a component before it does significant damage to the system or leaves the machine inoperable for an extended period of time. More accurate weather forecasting will also become a major contributor in optimizing service schedules for lower cost.
- **Develop low-cost foundations, anchors, and moorings:** Current shallow-water foundations have already reached a practical depth limit of 30 m, and anchor systems beyond that are derived from conservative and expensive oil and gas design practices. Cost-saving opportunities arise for wind power plants in deeper water with both fixed-bottom and floating turbine foundations, as well as for existing shallow-water designs in which value-engineering cost reductions can be achieved. Fixed-bottom systems comprising rigid lightweight substructures, automated mass-production fabrication facilities, and integrated mooring and piling deployment systems that minimize dependence on large sea vessels are possible low-cost options. Floating platforms will require a new generation of mooring designs that can be mass produced and easily installed.
- **Use resource modeling and remote profiling systems:** Offshore winds are much more difficult to characterize than winds over land. Analytical models are essential for managing risk during the initial

siting of offshore projects, but are not very useful by themselves for micrositing (Jimenez et al. 2005). Alternative methods are needed to measure wind speed and wind shear profiles up to elevations where wind turbines operate. This will require new equipment such as sonic detection and ranging (SODAR), light detection and ranging (LIDAR), and coastal RADAR-based systems that must be adapted to measure offshore wind from more stable buoy systems or from fixed bases. Some systems are currently under development but have not yet been proven (Antoniou et al. 2006). The results of an RD&D measurement program on commercial offshore projects could generate enough confidence in these systems to eliminate the requirement for a meteorological tower.

- **Increase offshore turbine reliability:** The current offshore service record is mixed, and as such, is a large contributor to high risk. A new balance between initial capital investment and long-term operating costs must be established for offshore systems. This new balance will have a significant impact on COE. Offshore turbine designs must place a higher premium on reliability and anticipation of on-site repairs than their land-based counterparts. Emphasis should be placed on avoiding large maintenance events that require expensive and specialized equipment. This can be done by identifying the root causes of component failures, understanding the frequency and cost of each event, and appropriately implementing design improvements (Stiesdal and Madsen 2005). Design tools, quality control, testing, and inspection will need heightened emphasis. Blade designers must consider strategies to offset the impacts of marine moisture, corrosion, and extreme weather. In higher latitudes, designers must also account for ice flows and ice accretion on the blades. Research that improves land-based wind turbine reliability now will have a direct impact on the reliability of future offshore machines.

- **Assess the potential of ultra-large offshore turbines:** Land-based turbines may have reached a size plateau because of transportation and erection limits. Further size growth in wind turbines will largely be pushed by requirements unique to offshore turbine development. According to a report on the EU-funded UpWind project, "Within a few years, wind turbines will have a rotor diameter of more than 150 m and a typical size of 8 MW–10 MW" (Risø National Laboratory 2005). The UpWind project plans to develop design tools to optimize large wind turbine components, including rotor blades, gearboxes, and other systems that must perform in large offshore wind plants. New size-enabling technologies will be required to push wind turbines beyond the scaling limits that constrain the current fleet. These technologies include lightweight composite materials and composite manufacturing, lightweight drivetrains, modular pole direct-drive generators, hybrid space frame towers, and large gearbox and bearing designs that are tolerant of slower speeds and larger scales. All of the weight-reducing features of the taller land-based tower systems will have an even greater value for very large offshore machines (Risø National Laboratory 2005).

RD&D Summary

The advancement of offshore technology will require the development of infrastructure and technologies that are substantially different from those employed in land-based installations. In addition, these advances would need to be tailored to U.S. offshore requirements, which differ from those in the European North Sea environment. Government leadership could accelerate baseline research and technology development to demonstrate feasibility, mitigate risk, and reduce regulatory and environmental barriers. Private U.S. energy companies need to take the technical and financial steps to initiate near-term development of offshore wind power technologies and bring them to sufficient maturity for large-scale deployment. Musial and Ram (2007) and Bywaters and colleagues (2005) present more detailed analyses of actions for offshore development.

2.6 Distributed Wind Technology

Q16

Distributed wind technology (DWT) applications refer to turbine installations on the customer side of the utility meter. These machines range in size from less than 1 kW to multimegawatt, utility-scale machines, and are used to offset electricity consumption at the retail rate. Because the WinDS deployment analysis does not currently segregate DWT from utility deployment, DWT applications are part of the land-based deployment estimates in the 20% Wind Energy Scenario.

Historically, DWT has been synonymous with small machines. The DWT market in the 1990s focused on battery charging for off-grid homes, remote telecommunications sites, and international village power applications. In 2000, the industry found a growing domestic market for behind-the-meter wind power, including small machines for residential and small farm applications and multimegawatt-scale machines for larger agricultural, commercial, industrial, and public facility applications. Although utility-scale DWT requirements are not distinguishable from those for other large-scale turbines, small machines have unique operating requirements that warrant further discussion.

2.6.1 Small Turbine Technology

Q17

Until recently, three-bladed upwind designs using tail vanes for passive yaw control dominated small wind turbine technology (turbines rated at less than 10 kW). Furling, or turning the machine sideways to the wind with a mechanical linkage, was almost universally used for rotor overspeed control. Drivetrains were direct-drive, permanent-magnet alternators with variable-speed operation. Many of these installations were isolated from the grid. Today, there is an emerging technology trend toward grid-connected applications and nonfurling designs. U.S. manufacturers are world leaders in small wind systems rated at 100 kW or less, in terms of both market and technology.

Turbine technology begins the transition from small to large systems between 20 kW and 100 kW. Bergey Windpower (Norman, Oklahoma) offers a 50 kW turbine that uses technology commonly found in smaller machines, including furling, pultruded blades, a direct-drive, permanent-magnet alternator, and a tail vane for yaw control. Distributed Energy Systems offers a 100 kW turbine that uses a direct-drive, variable-speed synchronous generator. Although most wind turbines in the 100 kW range have features common to utility-scale turbines, including gearboxes, mechanical brakes, induction generators, and upwind rotors with active yaw control, Endurance Windpower (Spanish Fork, Utah) offers a 5 kW turbine with such characteristics.

For small DWT applications, reliability and acoustic emissions are the prominent issues. Installations usually consist of a single turbine. Installations may also be widely scattered. So simplicity in design, ease of repair, and long maintenance and inspection intervals are important. Because DWT applications are usually close to workplaces or residences, limiting sound emissions is critical for market acceptance and zoning approvals. DWT applications are also usually located in areas with low wind speeds that are unsuitable for utility-scale applications, so DWT places a premium on low-wind-speed technologies.

The cost per kW of DWT turbines is inversely proportionate with turbine size. Small-scale DWT installation costs are always higher than those for utility-scale installations because the construction effort cannot be amortized over a large number of turbines. For a 1 kW system, hardware costs alone can be as high as $5,000 to $7,000/kW. Installation costs vary widely because of site-specific factors such as zoning and/or permitting costs, interconnection fees, balance-of-station costs, shipping, and the extent of do-it-yourself participation. Five-year warranties are now the industry standard for small wind turbines, although it is not yet known how this contributes to turbine cost. The higher costs of this technology are partially offset by the ability to compete with retail electricity rates. In addition, small turbines can be connected directly to the electric distribution system, eliminating the need for an expensive interconnection between the substation and the transmission.

Tower and foundation costs make up a larger portion of DWT installed cost, especially for wind turbines of less than 20 kW. Utility-scale turbines commonly use tapered tubular steel towers. However, for small wind turbines, multiple types, sources, and heights of towers are available.

2.6.2 Technology Trends

Q18

Recent significant developments in DWT systems less than 20 kW include the following:

- **Alternative power and load control strategies:** Furling inherently increases sound levels because the cross-wind operation creates a helicopter-type chopping noise. Aerodynamic models available today cannot accurately predict the rotor loads in the highly skewed and unsteady flows that occur during the furling process, complicating design and analysis. Alternative development approaches include soft-stall rotor-speed control, constant-speed operation, variable-pitch blades, hinged blades, mechanical brakes, and centrifugally actuated blade tips. These concepts offer safer, quieter turbines that respond more predictably to high winds, gusts, and sudden wind direction changes.
- **Advanced blade manufacturing methods:** Blades for small turbines have been made primarily of fiberglass by hand lay-up manufacturing or pultrusion. The industry is now pursuing alternative manufacturing techniques, including injection, compression, and reaction injection molding. These methods often provide shorter fabrication time, lower parts costs, and increased repeatability and uniformity, although the tooling costs are typically higher.

- **Rare-earth permanent magnets:** Ferrite magnets have long been the staple in permanent-magnet generators for small wind turbines. Rare-earth permanent magnets are now taking over the market with Asian suppliers offering superior magnetic properties and a steady decline in price. This enables more compact and lighter weight generator designs.
- **Reduced generator cogging:** Concepts for generators with reduced cogging torque (the force needed to initiate generator rotation) are showing promise to reduce cut-in wind speeds. This is an important advancement to improve low-wind-speed turbine performance and increase the number of sites where installation is economical.
- **Induction generators:** Small turbine designs that use induction generators are under development. This approach, common in the early 1980s, avoids the use of power electronics that increase cost and complexity, and reduce reliability.
- **Grid-connected inverters:** Inverters used in the photovoltaics market are being adapted for use with wind turbines. Turbine-specific inverters are also appearing in both single- and three-phase configurations. Another new trend is obtaining certification of most inverters by Underwriters Laboratories and others for compliance with national interconnection standards.
- **Reduced rotor speeds:** To reduce sound emissions, turbine designs with lower tip-speed ratios and lower peak-rotor speeds are being pursued.
- **Design standards and certification:** The industry is increasing the use of consensus standards in its turbine design efforts for machines with rotor swept areas under 200 m^2 (about 65 kW rated power). In particular, IEC Standard 61400-2 Wind Turbines – Part 2: Design Requirements of Small Wind Turbines. Currently, however, a limited number of wind turbines have been certified in compliance with this standard because of the high cost of the certification process. To address this barrier, a Small Wind Certification Council has been formed in North America to certify that small wind turbines meet the requirements of the draft AWEA standard that is based on the IEC standard (AWEA 1996–2007).

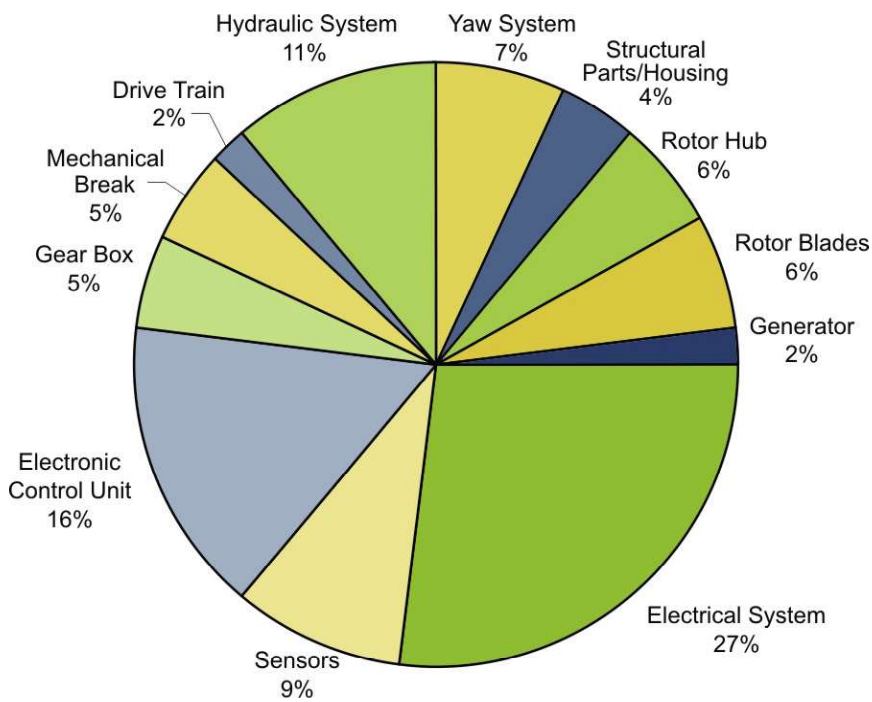
2.7 Summary of Wind Technology Development Needs

Wind technology must continue to evolve if wind power is to contribute more than a few percentage points of total U.S. electrical demand. Fortunately, no major technology breakthroughs in land-based wind technology are needed to enable a broad geographic penetration of wind power into the electric grid. However, there are other substantial challenges (such as transmission and siting) and significant costs associated with increased penetration, which are discussed in other chapters of this report. No improvement in cost or efficiency for a single component can achieve the cost reductions or improved capacity factor that system-level advances can achieve.

The wind capacity factor can be increased by enlarging rotors and installing them on taller towers. This would require advanced materials, controls, and power systems that can significantly reduce the weight of major components. Capital costs would also be brought down by the manufacturing learning curve that is associated with continued technology advancement and by a nearly fivefold doubling of installed capacity.

The technology development required to make offshore wind a viable option poses a substantial potential risk. Offshore wind deployment represents a significant fraction of the total wind deployment necessary for 20% wind energy by 2030. Today's European shallow-water technology is still too expensive and too difficult to site in U.S. waters. Deepwater deployment would eliminate visual esthetics concerns, but the necessary technologies have yet to be developed, and the potential environmental impacts have yet to be evaluated. To establish the offshore option, work is needed to develop analysis methods, evaluate technology pathways, and field offshore prototypes.

Figure 2-17. Types of repairs on wind turbines from 2.5 kW to 1.5 MW



Today's market success is the product of a combination of technology achievement and supportive public policy. A 20% Wind Scenario would require additional land-based technology improvements and a substantial development of offshore technology. The needed cost and performance improvements could be achieved with innovative changes in existing architectures that incorporate novel advances in materials, design approaches, control strategies, and manufacturing processes. Risks are mitigated with standards that produce reliable equipment and full-scale testing that ensures the machinery meets the design requirements.

The 20% Wind Scenario assumes a robust technology that will produce cost-competitive generation with continued R&D investment leading to capital cost reduction and performance improvement. Areas where industry can focus RD&D efforts include those which require the most frequent repairs (see Figure 2-17). Such industry efforts, along with government-supported RD&D efforts, will support progress toward achieving two primary wind technology objectives:

- Increasing capacity factors by placing larger rotors on taller towers (this can be achieved economically only by using lighter components and load-mitigating rotors that reduce the integrated tower-top mass and structural loads; reducing parasitic losses throughout the system can also make gains possible), developing advanced controls, and improving power systems.

- Reducing the capital cost with steady learning-curve improvements driven by innovative manufacturing improvements and a nearly fivefold doubling of installed capacity

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Chapter 3. Manufacturing, Materials, and Resources

Q19

A 20% Wind Energy Scenario would support expansion of domestic manufacturing and related employment. Production of several key materials for wind turbines would require substantial but achievable growth.

Stakeholders and decision makers need to know whether the effort to achieve a generation mix with 20% wind energy by 2030 might be constrained by raw materials availability, manufacturing capability, or labor availability. This chapter examines the adequacy of these critical resources.

Over the past five years, the wind industry in the United States has grown by an average of 22% annually. In 2006 alone, America's wind power generating capacity increased by 27%.

The U.S. wind energy industry invested approximately $4 billion to build 2,454 MW of new generating capacity in 2006, making wind the second largest source of new power generation in the nation—surpassed only by natural gas—for the second year in a row. Recently installed wind farms increased cumulative installed U.S. wind energy capacity to 13,884 MW—well above the 10,000 MW milestone reached in August 2006 (AWEA 2007). On average, 1 MW of wind power produces enough electricity to power 250 to 300 U.S. homes.

Based on estimates released by the U.S. Department of Energy (DOE) Energy Information Administration (EIA 2006), annual electricity consumption in the United States is expected to grow at a rate of 1.3% annually—from 3.899 billion megawatt-hours (MWh) in 2006 to about 5.368 billion MWh in 2030. Although wind energy supplied approximately 0.8% of the total electricity in 2006, more and larger wind turbines can help to meet a growing demand for electricity. (See the Glossary in Appendix E for explanations of wind energy capacity and measurement units.)

The most common large turbines currently in use have a rated capacity of between 1 MW and 3 MW, with rotor diameters between 60 m and 90 m, tower heights between 60 m and 100 m, and capacity factors between 30% and 40% (capacity factor is an indicator of annual energy production). Although currently installed machines are expected to operate through 2030, larger turbines (with capacity factors that increase over time, as discussed in Chapter 2) are expected to become more common as offshore technology advances are transferred to land-based turbines. These larger turbines could reach rated power between 4 MW and 6 MW with capacity factors between 40% and 50%.

3

To estimate the raw materials and investments needed to support the 20% Wind Scenario, industry leaders have assumed that most of the wind turbines used in the next two to three decades will be in the 1 MW to 3 MW class, with a modest contribution of the larger-sized machines (see Chapter 2). Today, approximately 2,000 turbines are installed each year, but that figure is expected to rise and to level out at about 7,000 turbines per year by 2017.

3.1 Raw Materials Requirements

Wind turbines are built in many sizes and configurations, with the larger sizes utilizing a wide range of materials. Reducing the weight and cost of the turbines is key to making wind energy competitive with other power sources. Throughout the next few decades, business opportunities are expected to expand in wind turbine components and materials manufacturing. To reach the high levels of wind energy associated with the 20% Wind Scenario, materials usage will also need to increase considerably, even as new technologies that improve component performance are introduced.

To estimate the raw materials required for the 20% Wind Scenario, this analysis focuses on the most important materials used in building a wind turbine today (such as steel and aluminum) and on main turbine components. Table 3-1 shows the percentage of different materials used in each component and each component's percentage of total turbine weight. The table applies to 1.5 MW turbines MW and larger.

Table 3-2 uses the materials consumption model in Table 3-1 to further describe the raw materials required to reach manufacturing levels of about 7,000 turbines per year. This analysis assumes that turbines will become lighter, annual installation rates will level off to roughly 7,000 turbines per year by 2017, and installation will continue at that rate through 2030. Approximately 100,000 turbines will be required to produce 20% of the nation's electricity in 2030.

No single component dominates a wind turbine's total cost, which is generally split evenly among the rotor, electrical system, drivetrain, and tower. The technological progress described in Chapter 2, however, could significantly reduce costs (e.g., through the use of lighter weight components for blades and towers).

The availability of critical resources is crucial for large-scale manufacturing of wind turbines. The most important resources are steel, fiberglass, resins (for composites and adhesives), blade core materials, permanent magnets, and copper. The production status of these materials is reviewed in the following list:

- **Steel:** The steel needed for additional wind turbines is not expected to have a significant impact on total steel production. (In 2005, the United States produced 93.9 million metric tons of steel, or 8% of the worldwide total.) Although steel will be required for any electricity generation technology installed over the next several decades, it can be recycled. As a result, replacing a turbine after 20+ years of service would not significantly affect the national steel demand because recycled steel can be used in other applications where high-quality steel is not required (Laxson, Hand, and Blair 2006).

Table 3-1. Main components and materials used in a wind turbine (%)

1.5 MW	Weight %	Permanent Magnet	Concrete	Steel	Aluminum	Copper	GRP	CRP	Adhesive	Core	TOTAL
Rotor											
Hub	6.0			100							100.0
Blades	7.2			2			78		15	5	100.0
Nacelle											
Gearbox	10.1			96	2	2					100.0
Generator	3.4			65		35					100.0
Frame	6.6			85	9	3	3				100.0
Tower	66.7		2	98							
	100.0	**0.0**	**1.3**	**89.1**	**0.8**	**1.6**	**5.8**	**0.0**	**1.1**	**0.4**	**100.0**
4 MW		**Permanent Magnet**	**Concrete**	**Steel**	**Aluminum**	**Copper**	**GRP**	**CRP**	**Adhesive**	**Core**	
Rotor											
Hub	6.00			100							100.0
Blades	7.6			2			68	10	15	5	100.0
Nacelle											
Gearbox	10.10			96	2	2					100.0
Generator	2.7	3		93		4					100.0
Frame	6.60			85	9	3	3				100.0
Tower	67.00		2	98							
	100.0	**0.08**	**1.34**	**89.63**	**0.80**	**0.51**	**5.37**	**0.76**	**1.14**	**0.38**	**100.0**

Notes: Tower includes foundation. GRP = glass-fiber-reinforced plastic. CRP = carbon fiber reinforced plastic
Source: Sterzinger and Svrcek (2004)

Table 3-2. Yearly raw materials estimate (thousands of metric tons)

Q20

Year	kWh/kg	Permanent Magnet	Concrete	Steel	Aluminum	Copper	GRP	CRP	Adhesive	Core
2006	65	0.03	1,614	110	1.2	1.6	7.1	0.2	1.4	0.4
2010	70	0.07	6,798	464	4.6	7.4	29.8	2.2	5.6	1.8
2015	75	0.96	16,150	1,188	15.4	10.2	73.8	9.0	15.0	5.0
2020	80	2.20	37,468	2,644	29.6	20.2	162.2	20.4	33.6	11.2
2025	85	2.10	35,180	2,544	27.8	19.4	156.2	19.2	31.4	10.4
2030	90	2.00	33,800	2,308	26.4	18.4	152.4	18.4	30.2	9.6

Notes: kg = kilograms; GRP = glass-fiber-reinforced plastic. CRP = carbon fiber reinforced plastic
Source: Sterzinger and Svrcek (2004)

- **Fiberglass:** Additional fiberglass furnaces would be needed to build more wind turbines. Primary raw materials for fiberglass (sand) are in ample supply, but availability and costs are expected to fluctuate for resins, adhesives, and cores made from the petroleum-based chemicals that are used to impregnate the fiberglass (Laxson, Hand, and Blair 2006).
- **Core:** End-grain balsa wood is an alternative core material that can replace the low-density polymer foam used in blade construction. Availability of this wood might be an issue based on the growth rate of balsa trees relative to the projected high demand.
- **Carbon fiber:** Current global production of commercial-grade carbon fiber is approximately 50 million pounds (lb) per year. The use of carbon fiber in turbine blades in 2030 alone would nearly double this demand. To achieve such drastic industry scale-up, changes to carbon fiber production technologies, production facilities, packaging, and emissions-control procedures will be required.

- **Permanent magnets:** By eliminating copper from the generator rotor and using permanent magnets, which are becoming more economically feasible, it is possible to build smaller and lighter generators. World magnet production in 2005 was about 40,000 metric tons, with about 35,000 metric tons produced in China. Although supply is not expected to be restricted, significant additions to the manufacturing capability would be required to meet the demand for wind turbines and other products (Trout 2002; Laxson, Hand, and Blair 2006).
- **Copper:** Although wind turbines use significant amounts of copper, the associated level of demand still equates to less than 4% of the available copper. This demand level, would not have a significant impact on national demand (U.S. refined copper consumption was 2.27 million metric tons in 2005). Although copper ranks third after steel and aluminum in world metals consumption, global copper production is adequate to satisfy growing demands from the wind industry. However, in recent years copper prices have escalated more quickly than inflation, which could affect turbine costs.

Despite the demand and supply status of these materials, new component developments are expected to significantly change material requirements. Generally, trends are toward using lighter-weight materials, as long as the life-cycle costs are low. In addition to the findings of Ancona and McVeigh (2001; described in the Materials Usage Analysis sidebar), other trends in turbine components are outlined in the subsections that follow.

Material Usage Analysis
(Ancona and McVeigh 2001)

- Turbine material usage is, and will continue to be, dominated by steel.
- Opportunities exist for introducing aluminum or other lightweight composites, provided that cost, strength, and fatigue requirements can be met.
- GRP is expected to continue to be used for blades.
- The use of carbon fiber might help reduce weight and cost.
- Low costs and high reliability remain the primary drivers.
- Variable-speed generators will become more common.
- Permanent-magnet generators on larger turbines will increase the need for magnetic materials.
- Simplification of the nacelle machinery might reduce raw material costs and also increase reliability.

Evolution of Rotors

Most rotor blades in use today are built from glass-fiber-reinforced plastic (GRP). Steel and various composites such as carbon filament-reinforced plastic (CFRP) are also used. As the rotor size increases for larger machines, the trend will be toward high-strength, fatigue-resistant materials. Composites involving steel, GRP, CFRP, and possibly other new materials will likely come into use as turbine designs evolve.

Changes to Machine Heads

The machine head contains an array of complex machinery including yaw drives, blade-pitch-change mechanisms, drive brakes, shafts, bearings, oil pumps and coolers, controllers, a bedplate, the drivetrain, the gearbox, and an enclosure. Design simplifications and innovations are anticipated in each element of the machine head.

3.2 MANUFACTURING CAPABILITY

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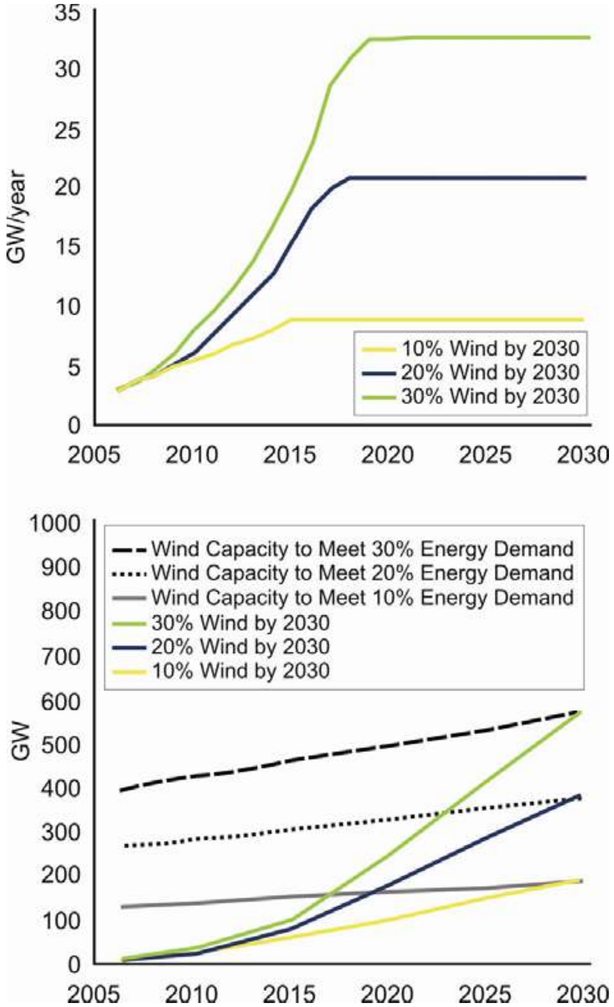
In principle, a sustainable level of annual wind turbine installation would be best supported by a substantial domestic manufacturing base. However, if installation rates fluctuate greatly from one year to the next, manufacturing capability may not be able to grow or shrink as necessary. The National Renewable Energy Laboratory (NREL) created a simple model to explore sustainable installation rates that would maintain wind energy production at specific levels spanning several decades (Laxson, Hand, and Blair 2006).

NREL's study explored a number of alternative scenarios for annual wind power capacity expansion to understand their potential impact on wind energy installation and manufacturing rates. The results indicate that achieving the 20% Wind Scenario by 2030 would not overwhelm U.S. industry (Laxson, Hand, and Blair 2006).

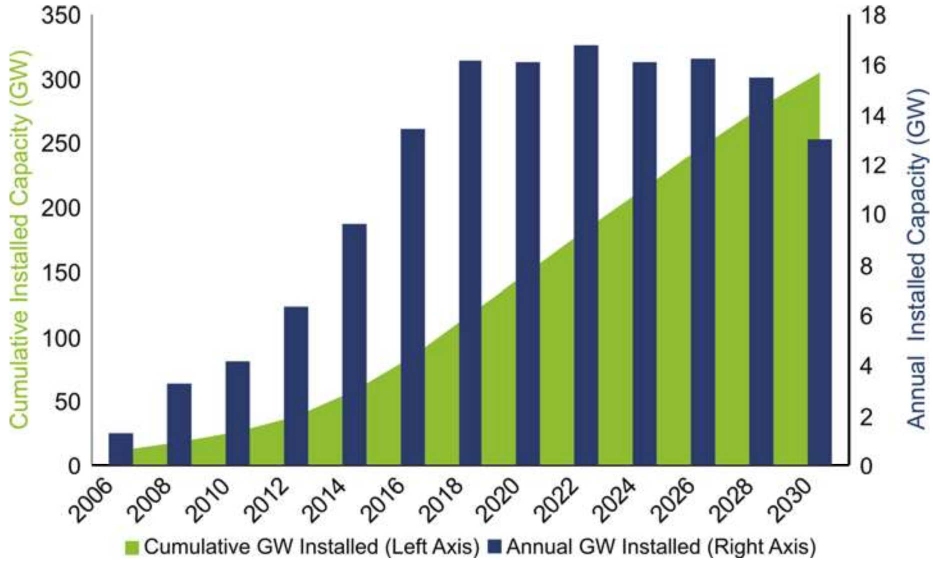
NREL's study assessed potential barriers that would prohibit near-term high wind penetration levels, such as manufacturing rates or resource limitations. To reach 20% electric generation from wind by 2030 in the United States, the authors noted, an annual installed capacity increase of about 20% would need to be sustained for a decade (Laxson, Hand, and Blair 2006). Figure 3-1 compares the installation rates required to meet three energy supply goals of 10%, 20%, and 30% of total national electrical energy production from wind by 2030. Figure 3-1(a) shows the annual rates and Figure 3-1(b) shows the cumulative capacity attained in each case. A manufacturing production level of 20 gigawatts (GW) per year by 2017—and maintained at this value thereafter—would reach levels close to 400 GW of wind energy capacity by 2030.

Figure 3-1. a. Annual installed wind energy capacity to meet 20% of energy demand. b. Cumulative installed wind energy capacity to meet 20% of energy demand.



NREL's study assumed that the wind plant capacity factor would not change from year to year or from location to location. This assumption provided an upper bound on the annual installation rate and cumulative capacity required to produce 20% of electricity demand. Alternatively, the 20% Wind Scenario evaluation assumes that plant capacity factors will increase modestly with experience and technology improvements (see Chapter 2). The 20% Scenario also accounts for regional variations in wind resources, as explained in Appendix A's detailed description of the analytic modeling approach employed. Note that when these refinements are included, the 20% curve in Figure 3-1(a) shifts downward, somewhat similar to that shown in Figure 3-2 on the next page.

Figure 3-2. Annual and cumulative installed wind energy capacity represented in the 20% Wind Scenario



This chapter discusses the materials and manufacturing needed to pursue the 20% Wind Scenario from 2007 through 2030 to meet the annual and cumulative installed capacity shown in Figure 3-2. This figure shows the forecasts for annual and cumulative installed wind energy capacity, which also forms the basis for estimates of new wind turbines and the raw materials required to produce them. In this scenario, annual installations climb more than 16 GW per year, and the total installed wind capacity increases to 305 GW by 2030. Between 2007 and 2030, 293 GW are installed. (For more details on the modeling approach used, see Appendix A.)

3.2.1 Current Manufacturing Facilities

A growing number of states and companies in the United States are ramping up capacity to manufacture wind turbines, or have the ability to do so. Jobs are expected to remain in the United States, but only if investments are made in certain components and in advanced manufacturing technologies. Appendix C describes the jobs and economic impacts associated with wind energy, including manufacturing, construction, and operational sectors of the wind industry.

A useful perspective on growing manufacturing requirements is provided by a non-government organization study released in 2004 called *Wind Turbine Development: Location of Manufacturing Activity* (Sterzinger and Svrcek 2004). This study investigated the current and future U.S. wind manufacturing industry, both to determine the location of companies involved in wind turbine production and to examine limitations to a rapidly expanding wind business. The report covered four census regions (the Midwest, Northeast, South, and West) and divided turbine manufacturing into 20 separate components. These components were grouped into five categories, as shown in Table 3-3. The table also shows the locations of U.S. wind turbine component manufacturers in 2004, broken down by region. Among the 106 companies surveyed, about 90 companies directly manufacture components for utility-scale wind turbines, with utility scale being roughly defined as 1 MW or greater.

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Table 3-3. Locations of U.S. wind turbine component manufacturers

Region	Division	Rotor	Nacelle and Controls	Gearbox & Drivetrain	Generator & Power Electronics	Tower	Division Total
Midwest	East North Central	6	5	8	1	2	22
	West North Central	1	0	1	1	8	11
Northeast	Middle Atlantic	3	4	4	5	1	17
	New England	0	6	0	2	0	8
South	East South Central	0	0	0	0	2	2
	South Atlantic	3	2	1	1	2	9
	West South Central	4	5	0	1	6	16
West	Mountain	1	0	0	1	0	2
	Pacific	5	4	2	4	4	19
	Component Total:	**23**	**26**	**16**	**16**	**25**	**106**

(Sterzinger and Svrcek 2004)

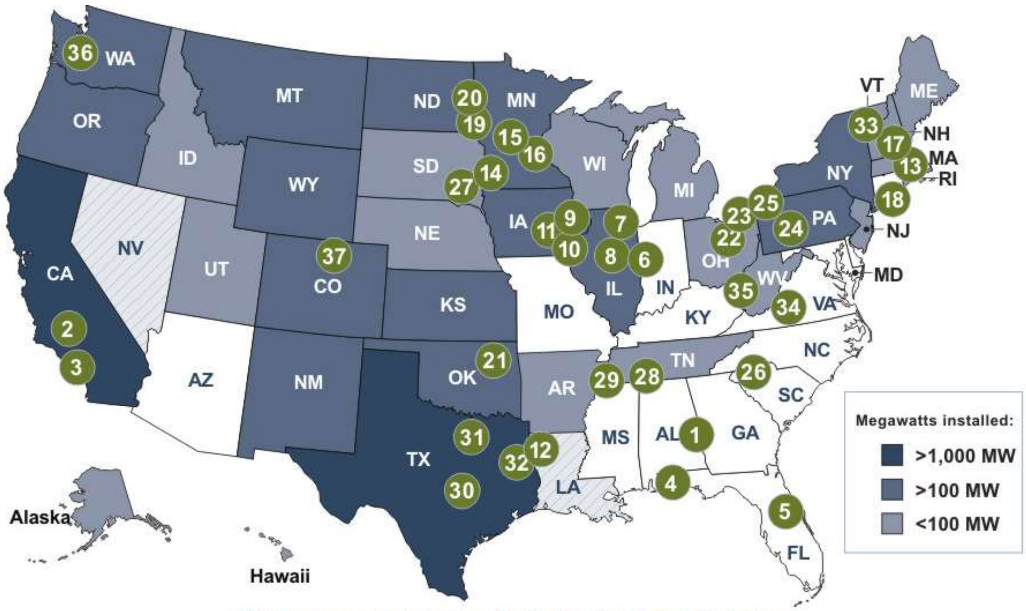
Figure 3-3 on the next page shows the locations of a number of the current manufacturers of wind turbines and components. These firms are widely distributed around the country and some are located in regions with, as yet, little wind power development.

A large national investment in wind would likely spread beyond these active companies. To identify this potential, the North American Industrial Classification System (NAICS; http://www.census.gov/epcd/www/naics.html) was searched to identify companies operating under relevant industry codes. The manufacturing activity related to wind power development is substantial and widely dispersed (Sterzinger and Svrcek 2004). As Table 3-4 shows, more than 16,000 firms are currently producing products under one or more of the NAICS codes that include

Table 3-4. U.S. Manufacturing firms with technical potential to enter wind turbine component market

NAICS Code	Code Description	Total Employees	Annual Payroll ($1000s)	Number of Companies
326199	All Other Plastics Products	501,009	15,219,355	8,174
331511	Iron Foundries	75,053	3,099,509	747
332312	Fabricated Structural Metal	106,161	3,975,751	3,033
332991	Ball and Roller Bearings	33,416	1,353,832	198
333412	Industrial and Commercial Fans and Blowers	11,854	411,979	177
333611	Turbines, and Turbine Generators, and Turbine Generator Sets	17,721	1,080,891	110
333612	Speed Changer, Industrial	13,991	539,514	248
333613	Power Transmission Equip.	21,103	779,730	292
334418	Printed Circuits and Electronics Assemblies	105,810	4,005,786	716
334519	Measuring and Controlling Devices	34,499	1,638,072	830
335312	Motors and Generators	62,164	2,005,414	659
335999	Electronic Equipment and Components, NEC	42,546	1,780,246	979
Total		**1,025,327**	**35,890,079**	**16,163**

Figure 3-3. Examples of manufacturers supplying wind equipment across the United States



Wind power creates manufacturing jobs even in regions like the Southeast that do not have a large wind resource.

1 Vectorply. Phenix City, AL (composites for blades)
2 GE Energy, Tehachapi, CA (wind turbine manufacturing facility)
3 Bragg Crane & Rigging Service, Long Beach, CA (cranes, rigging, transportation)
4 GE Energy, Pensacola, FL (blade technology development)
5 Mitsubishi Power Systems, Lake Mary, FL (gear boxes)
6 White Construction Inc., Clinton, IN (construction services)
7 Winergy Drive Systems Corporation, Elgin, IL (gear units, generators, power converters)
8 Trinity Industries, Clinton, IL (towers)
9 Clipper Windpower, Cedar Rapids, IA (turbine manufacturing, assembly)
10 Siemens, Fort Madison, IA (blades)
11 Acciona Energia, West Branch, IA (planned) (turbine manufacturing)
12 Beaird Industries, Shreveport, LA (towers, tower flanges and bolts)
13 Second Wind Inc., Somerville, MA (anemometers, electronic controllers, sensors/data loggers)
14 Suzlon Wind Energy, Pipestone, MN (blade manufacture, turbine assembly)
15 D.H. Blattner & Sons, Avon, MN (construction)
16 M.A. Mortenson Co., Minneapolis, MN (construction)
17 Hendrix Wire & Cable Inc., Milford, NH (cables to substations)
18 Hailo LLC, Holbrook, NY (ladder and lift systems)
19 DMI Industries, West Fargo, ND (towers)
20 LM Glasfiber, Grand Forks, ND (blades)
21 Trinity Structural Towers, Tulsa, OK (towers)
22 Owens Corning Composites, Granville, OH (composites for blades)
23 Hamby Young, Aurora, OH (substations and high voltage applications)
24 Gamesa, Ebensburg, PA (blade, nacelle, tower manufacturing)
25 GE Energy, Erie, PA (wind turbine components)
26 GE Energy, Greenville, SC (turbine assembly plant)
27 Knight & Carver, Howard, SD (blade manufacturing)
28 Aerisyn Inc, Chattanooga, TN (towers)
29 Thomas & Betts Corp., Memphis, TN (towers, tower flange and bolts)
30 DeWind, Inc./TECO Westinghouse, Round Rock, TX (wind turbine manufacturing)
31 Trinity Structural Towers, Fort Worth, TX (towers)
32 CAB Incorporated, Nacogdoches, TX (blade extender, hub, nacelle frame, tower flange and bolts)
33 NRG Systems, Hinesburg, VT (anemometers, sensors/data loggers)
34 GE Energy, Salem, VA (wind turbine components)
35 Tower Logistics, Huntington, WV (lifts for turbines)
36 PowerClimber, Seattle, WA (traction hoists, rigging equipment)
37 Vestas, Windsor, CO (planned) (blade and turbine manufacturing)

manufacture of wind components. These firms are spread across all 50 states. They are concentrated, however, in the most populous states and the states that have suffered the most from loss of manufacturing jobs. The 20 states that would likely receive the most investment and the most new manufacturing jobs from wind power expansion account for 75% of the total U.S. population, and 76% of the manufacturing jobs lost in the last 3.5 years.

A 2006 NGO report entitled "*Renewable Energy Potential: A Case Study of Pennsylvania* (Sterzinger and Stevens 2006) identified the bottlenecks in the component supply chain. Bottlenecks were identified for various components, but obtaining gearbox components was particularly problematic. Currently, only a few manufacturers in the world deliver gearboxes for large wind turbines. Additional investments will be required to support the development of a gearbox industry specifically for large wind applications. Investments will also be needed to expand the manufacture of large bearings and large castings.

The wind equipment manufacturing sector also faces trade-offs between using domestic or foreign manufacturing facilities. An advantage to domestic operations is a reduction reducing the significant transportation costs of moving large components such as blades and towers. Manufacturing many significant wind turbine components is also a labor-intensive process. With U.S. labor wage rates at higher levels than those paid in many other countries, manufacturers have naturally been drawn to setting up their factories outside the United States (e.g., in Mexico and China). One wind blade manufacturer with significant international manufacturing experience estimates that, to make a U.S. factory competitive, the labor hours per blade would need to be reduced by a factor of 30%–35%. To ensure that the bulk of these manufacturing jobs stay in the United States, automation and productivity gains through the development of advanced manufacturing technology are needed. These gains will allow the higher U.S. wage rates to be competitive.

To attract these jobs, a number of U.S. states have set aside funds for RD&D, with plans to collaborate with industry and the federal government on a cost-shared basis. Collaboration among state, industry, and federal programs on advanced manufacturing technology can create competitive U.S. factories and provide better job security for U.S. employees.

3.2.2 Ramping Up Energy Industries

In the United States, several industries have experienced large rates of growth over a short period of time. The power plants most commonly used to produce electricity around the world—such as thermal power stations fired with coal, gas or oil, or nuclear reactors—are large in scale. Nuclear power stations, developed mainly since the middle of the twentieth century, have now reached a penetration of 17.1% in the world's power supply. Worldwide, nuclear power plant installations saw a 17% annual growth rate between 1960 and 1997 (BTM 1999). Despite a halt in new nuclear plant licensing in the early 1980s, U.S. nuclear plants generate about 20% of the nation's electrical energy, and have done so for the last decade or more. The history of nuclear power shows that it is possible to achieve substantial levels of penetration over two to three decades with a new technology.

Even though the time horizon of the 20% Wind Scenario is consistent with the historical development of nuclear power, it is nonetheless difficult to directly compare penetration patterns for nuclear power that is typically about 1,000 MW and wind power technology. A wind turbine is a smaller-scale technology that has a current typical commercial unit size of 2 MW–3 MW. Despite the smaller scales of wind power, its modularity makes it ideal for all sizes of installations—from a single unit (2 MW–3 MW) to a large utility-scale wind farm (1,000 MW). On the supply side, serial production of large numbers of similar units can reduce manufacturing costs. These factors suggest that manufacturing ramp-up for wind turbines should be less daunting than ramp-up for nuclear power plant equipment.

Experiences with natural-gas-fired power plants over the past decade also provide important perspectives on the ability to rapidly expand manufacturing capability for wind power. From the early 1990s through the first half of the current decade, the U.S. electric sector experienced a rush toward new gas combined-cycle and combustion-turbine generation. This growth was driven by the expectation—now discounted—of continuing low natural gas prices. From 1999 through 2005, tens of gigawatts of natural gas power plants were manufactured and installed in the United States each year, with installations peaking in 2002 at more than 60 GW (Black & Veatch 2007). The experience with natural gas demonstrates that huge amounts of power generation equipment can be manufactured in the United States if sufficient market demand exists.

As Table 3-5 shows, Toyota North America exemplifies the manufacturing scale-up of a modular technology and capability that is possible in the United States. Toyota has continued to establish U.S. manufacturing capability since the mid-1980s, and automobiles, like wind turbines, require large quantities of steel, plastics, and electronic components. There is no indication that Toyota's domestic expansion caused any strain on the nation's manufacturing or materials-supply sectors. Today, the majority of vehicles Toyota sells in the U.S. are produced in this country.

Table 3-5. Toyota North America vehicle production and sales

Direct U.S. Employment (2005)	32,003 employees
2005 Payroll	$2,244,946,444
Cumulative U.S. Production	12,374,062 vehicles
Cumulative Sales	$272,390,226,806
U.S. Vehicle Sales (2005)	2,269,296 vehicles
U.S. Vehicle Production (2005)	1,393,100 vehicles
Average Engine Power 2004-2005	227 horsepower or 0.17 MW
2005 U.S. Production in Power Output Terms	275 million horsepower 236 million kW or 236 GW
2005 U.S. Sales in Power Output Terms	448 million horsepower 384 million kW or 384 GW

Source: Adapted from Toyota website data
http://www.toyota.com/about/operations/manufacturing/

Table 3-5 shows that Toyota's annual U.S. production, when expressed in terms of engine power output, increased to 236 GW by 2005. This annual production begins to approach in power capability the total amount of wind generation installed between 2007 and 2030 through realization of the 20% Wind Scenario.

3.3 LABOR REQUIREMENTS

Beyond the raw material and manufacturing facilities required to create wind turbines and components, a skilled labor force would be required. This staff would need a range of skills and experience to fill many new employment opportunities. The likely outcome from developing new capabilities and capacity would be expansion of manufacturing in areas currently capable of competing or development in locations where logistic advantages exist.

3.3.1 MAINTAINING AND EXPANDING RELEVANT TECHNICAL STRENGTH

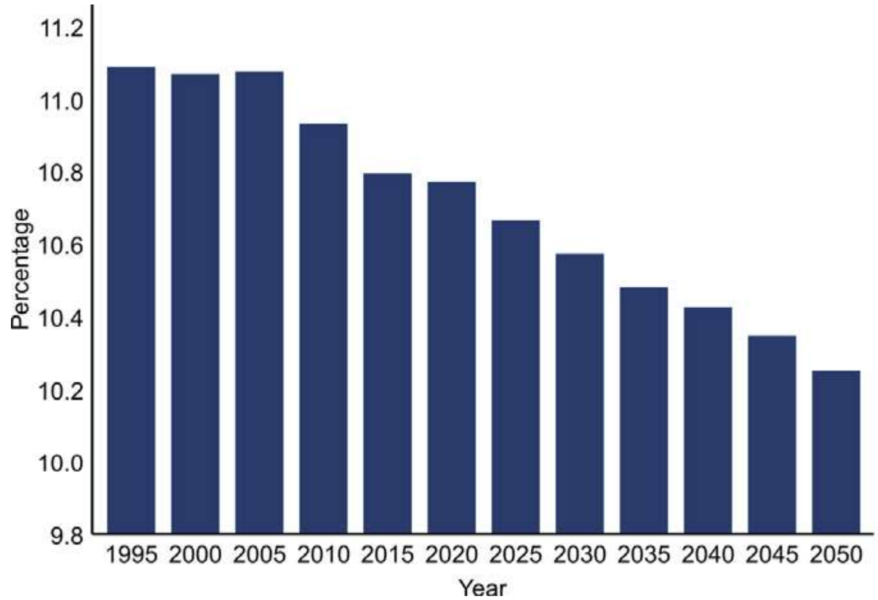
Major expansion of wind power in the United States would require substantial numbers of skilled personnel available to design, build, operate, maintain, and advance wind power equipment and technology. Toward this end, a number of educational programs are already offered around the nation, including those shown in Table 3-6.

Table 3-6. Wind technology-related educational programs around the United States today

School	Location	Degree or Program
Wind Energy Applications Training Symposium	Boulder, Colorado	Workshops for industry
Colorado State University	Fort Collins, Colorado	65 MW turbine on campus for research (engineering, environmental, etc.)
Advanced Technology Environmental Education Center: Sustainable Energy Education and Training	Bettencourt, Iowa	Workshops for upper level high school and community college technology instructors
Iowa Lakes Community College	Estherville, Iowa	One-year diploma for wind technician; two-year associate in applied science degree for wind technician
University of Massachusetts at Amherst: College of Engineering, and Renewable Energy Research Laboratory (becoming University of Massachusetts Wind Energy Center in late 2008)	Amherst, Massachusetts	MS and Ph.D. level engineering programs specializing in wind energy
Minnesota West Community and Technical College	Canby, Maine	Associate of applied science degree program in wind energy technology; diploma for wind energy mechanic; online certificate program for ”windsmith”
Southwestern Indian Polytechnic Institute	Albuquerque, New Mexico	Under development: Integration of renewable energy technology experiential learning into the electronics technology, environmental science, agricultural science, and natural resources certificate and degree programs
Mesalands Community College: North American Wind Research and Training Center	Tucumcari, New Mexico	Under development: Curriculum for operations and maintenance technician; two-year associate degree in wind farm management
Wayne Technical and Career Center	Williamson, New York	New Vision Renewable Energy Program for high school seniors
Columbia Gorge Community College	Hood River, Oregon	One-year certificate and two-year degree for renewable energy technician
Lane Community College	Eugene, Oregon	Two-year associate of applied science degree for energy management technician; two-year associate of applied science option for renewable energy technician
Texas Tech and other American universities: Wind Science & Engineering Research Center	Lubbock, Texas	Integrative graduate education and research traineeship
Lakeshore Technical College	Cleveland, Wisconsin	Associate degree in applied science; electromechanical technology with a wind system Technician track
Fond du Lac Tribal and Community College	Fond du Lac, Wisconsin	Clean Energy Technician Certificate Program

Although this is an excellent beginning, many more programs of a similar nature will be needed nationwide to satisfy the needs stemming from the 20% Wind Scenario. One concern is that the number of students in power engineering programs has been dropping in recent years. Currently, U.S. graduate power engineering programs produce about 500 engineers per year; in the 1980s, this number approached 2,000. In addition, the number of wind engineering programs in U.S. graduate schools is significantly lower than in Europe. This concern is echoed in Figure 3-4 below, which shows that the number of college graduates receiving

Figure 3-4. Projected percentage of 22-year-olds with a bachelor's degree in science and engineering through 2050



degrees in science and engineering has been declining, and that this trend is projected to continue for the foreseeable future (NSTC 2000).

Even the level of U.S. graduate programs is well below similar graduate programs in Europe (Denmark, Germany, etc). At this rate, the United States will be unable to provide the necessary trained talent and manufacturing expertise. Unless this trend is reversed, even with major new wind installations in the United States, most of the technology will be imported, and a significant portion of the economic gains will be foreign rather than domestic.

3.4 CHALLENGES TO 20% WIND ENERGY BY 2030

3.4.1 CHALLENGES

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Materials

Several key materials are crucial to the production of a wind turbine. The availability of some key raw materials—including fiberglass (about 9 metric tons required per megawatt of wind turbine capacity), resins, and permanent magnets—might potentially constrain the ability to develop an infrastructure producing high levels of wind power. To give perspective, the glass fiber requirements would be about half the level used domestically for roofing shingles (which is currently the largest consumer of fiberglass) and about double the amount now used in boat building.

Manufacturing

The 20% Wind Scenario would demand installations at a sustained growth rate of 20% annually for nearly a decade and then require maintaining that level of annual installations through 2030. For turbine companies, it is no longer simply a matter of where to establish new manufacturing capacity. Investment decisions must now address strategies for building out and securing supply lines on a global basis; a proactive stance is essential to operate successfully in an environment of rapidly growing and shifting demand for wind turbines (Hays, Robledo, and Ambrose 2006). Fortunately, the 20% Wind Scenario could be feasible even with the potential challenges related to the availability of raw material or increased manufacturing demands. For rapid growth of manufacturing capacity to be achieved, stable and consistent policies that encourage investment in these new sectors of activity are needed.

Labor

One potential gap in achieving high rates of wind energy development is the availability of a qualified work force. In a report published by the National Science and Technology Council (NSTC), as noted above, the percentage of 22-year-olds earning degrees in science and engineering will continue to drop in the next 40 years (NSTC 2000). More support from industry, trade organizations, and various levels of government could foster university programs in wind and renewable energy technology, preparing the work force to support the industry's efforts.

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