



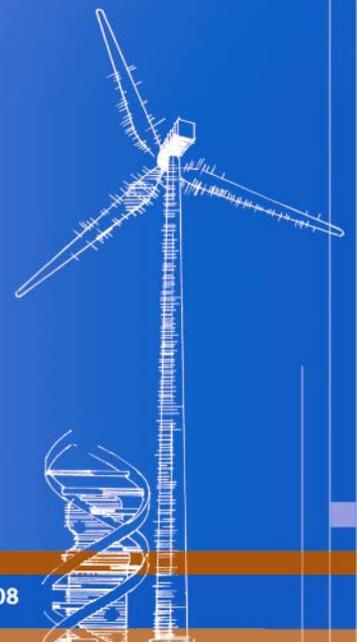
# The Future of Wind Energy Technology in the United States

R. Thresher and M. Robinson  
*National Renewable Energy Laboratory*

P. Veers  
*Sandia National Laboratories*

*Presented at the 2008 World Renewable Energy Congress  
Glasgow, Scotland, UK  
July 19–25, 2008*

**Conference Paper**  
**NREL/CP-500-43412**  
**October 2008**



NREL is operated for DOE by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08-GO28308



## NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy  
Office of Scientific and Technical Information  
P.O. Box 62  
Oak Ridge, TN 37831-0062  
phone: 865.576.8401  
fax: 865.576.5728  
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce  
National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22161  
phone: 800.553.6847  
fax: 703.605.6900  
email: [orders@ntis.fedworld.gov](mailto:orders@ntis.fedworld.gov)  
online ordering: <http://www.ntis.gov/ordering.htm>



# The Future of Wind Energy Technology in the United States

Robert Thresher<sup>1</sup>, Michael Robinson<sup>2</sup>, and Paul Veers<sup>3</sup>

<sup>1</sup> Wind Energy Research Fellow, National Renewable Energy Laboratory, Golden Colorado, USA; Telephone: 01-303-384-6922; e-mail: [Robert\\_Thresher@nrel.gov](mailto:Robert_Thresher@nrel.gov). This work has been authored by an employee or employees of the Midwest Research Institute under Contract No. DE-AC36-99GO10337 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes.

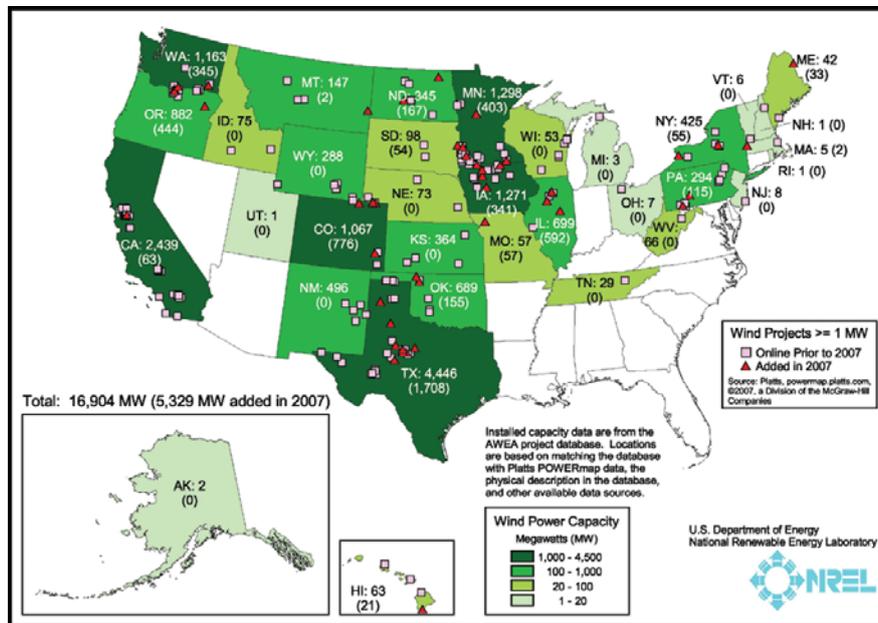
<sup>2</sup> Deputy Director of the National Wind Technology Center, National Renewable Energy Laboratory, Golden Colorado, USA; Telephone: 01-303-384-6947; e-mail: [Mike\\_Robinson@nrel.gov](mailto:Mike_Robinson@nrel.gov).

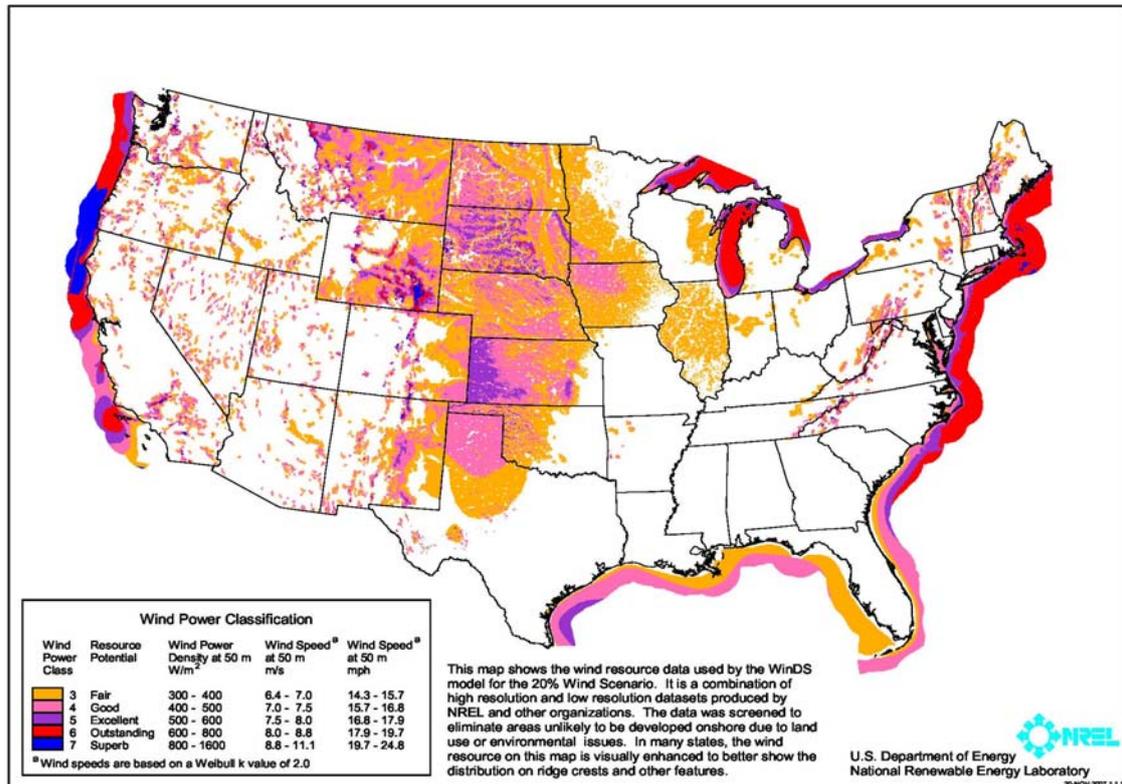
<sup>3</sup> Distinguished Member Technical Staff, Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

## 1 Introduction

Wind energy is one of the fastest growing electrical energy sources in the United States. The United States installed over 5,300 megawatts (MW) in 2007, and experts are forecasting as much to be

installed in 2008. The United States cumulative installed capacity as of December 31, 2007, was 16,904 MW. The state distribution of wind capacity is illustrated in Figure 1.





**FIGURE 2. The Wind Resource Potential at 50m on Land and Offshore.**

Wind capacity in the United States and in Europe has grown at a rate of 20% to 30% per year over the past decade. Despite this rapid growth, wind only provides for about 1% of total electricity consumption in the United States.

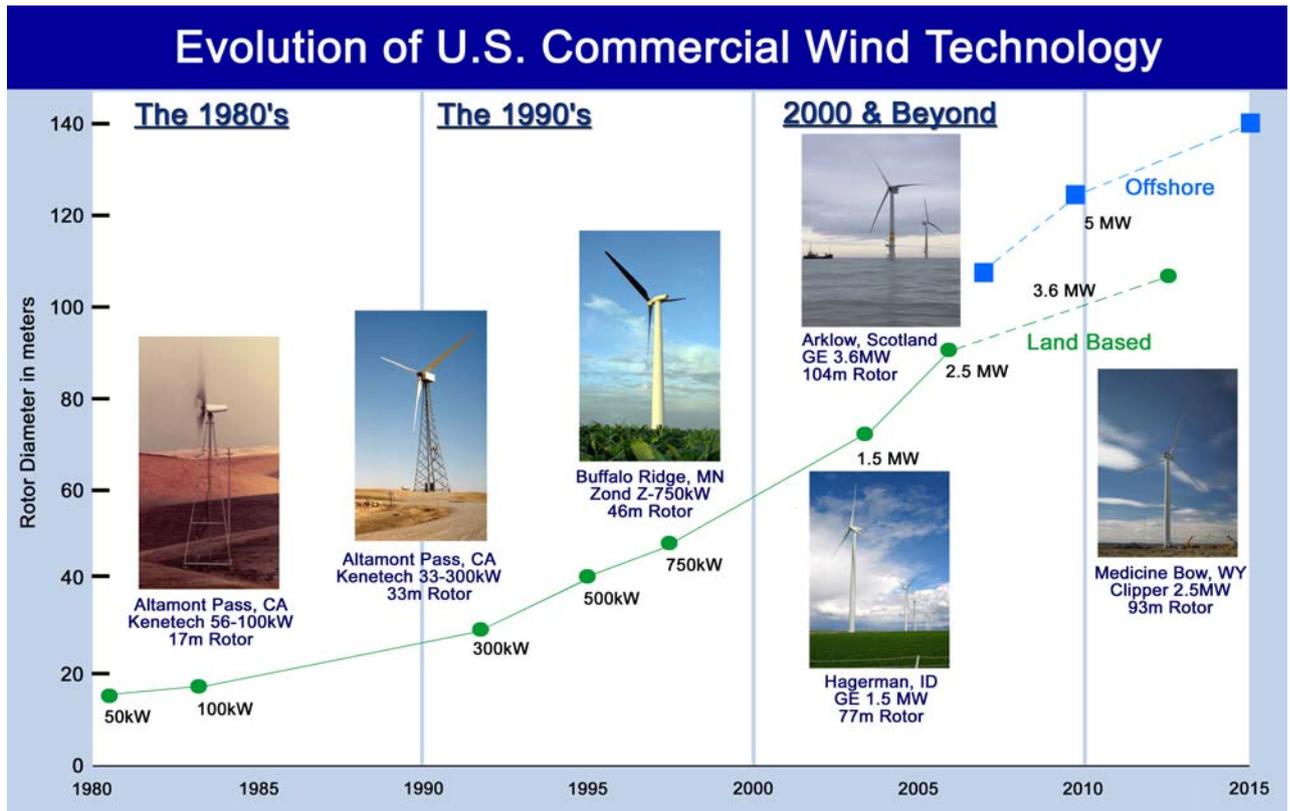
The United States is blessed with an abundance of wind energy potential. The land-based and offshore wind resource has been estimated to be sufficient to supply the electrical energy needs of the entire country several times over. The Midwest region, from Texas to North Dakota, is particularly rich in wind energy resources, as illustrated in Figure 2.

## 2 The Current Status of Wind Energy Technology in the United States

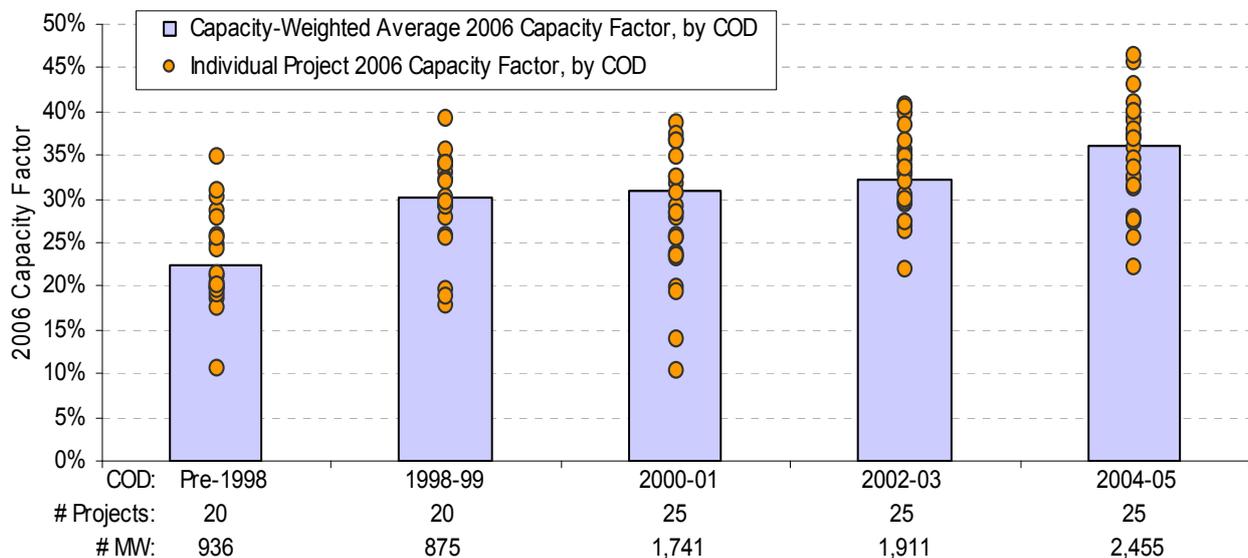
During the past 20 years, average wind turbine ratings have grown almost linearly, as shown in Figure 3. Current commercial machines are rated at 1.5 MW to 2.5 MW.

Each group of wind turbine designers predicted that their machines were as large as they will ever be. However, with each new generation of wind turbines, the size has increased along the linear curve and has achieved reductions in life-cycle cost of energy.

The long-term drive to develop larger turbines stems from a desire to take advantage of wind shear by placing rotors in the higher, much more energetic winds at a greater elevation above ground (wind speed increases with height above the ground). This is a major reason that the capacity factor of wind turbines installed in the United States has increased over time, as documented by Wisser and Bolinger<sup>1</sup>, and shown in Figure 4. However, there are constraints to this continued growth; in general, it costs more to build a larger turbine.



**FIGURE 3. The Development Path and Size Growth of Wind Turbines.**

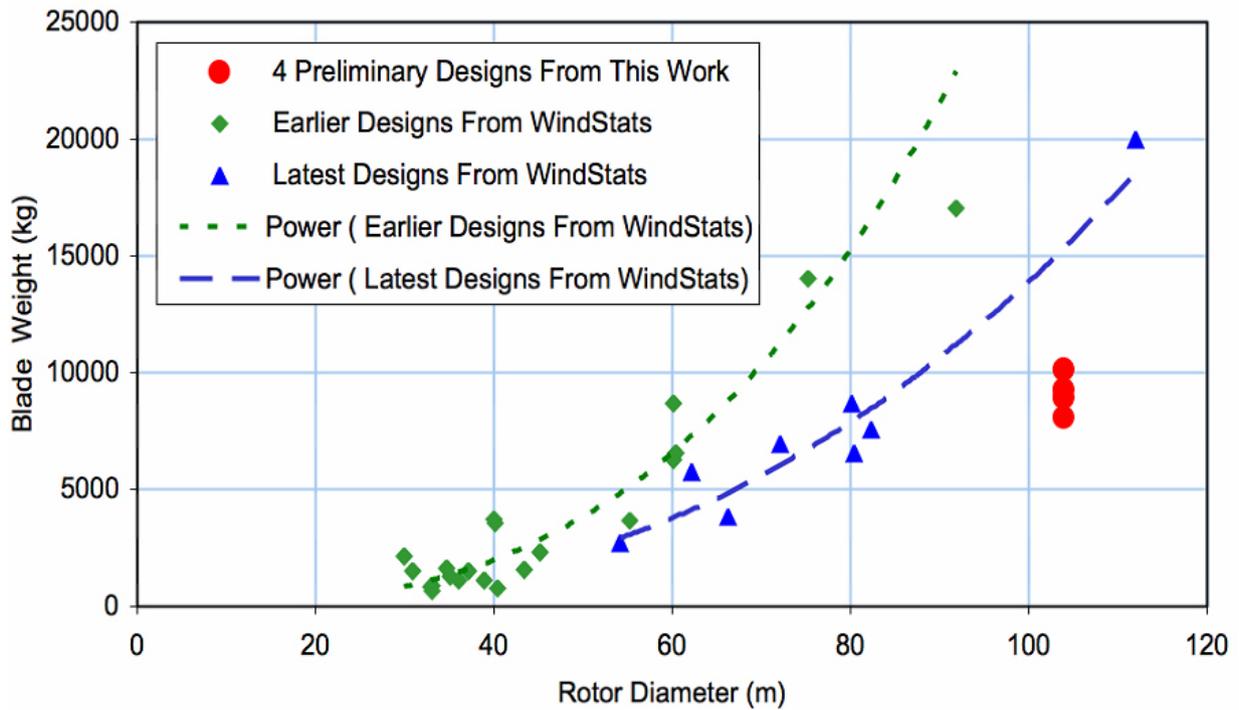


Source: Berkeley Lab database

**Figure 4. 2006 Project Capacity Factors by Commercial Operation Date (1).**

The primary argument for a size limit for wind turbines is based on the “square-cube law.” Roughly stated, it says that “as a wind turbine rotor increases 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 changing the design rules with increasing size



**FIGURE 5. WindPACT (2) Study Results Indicating the Lowering of Growth in Blade Weight Due to the Introduction of New Technology**

and removing material or by using material more efficiently to trim weight and cost.

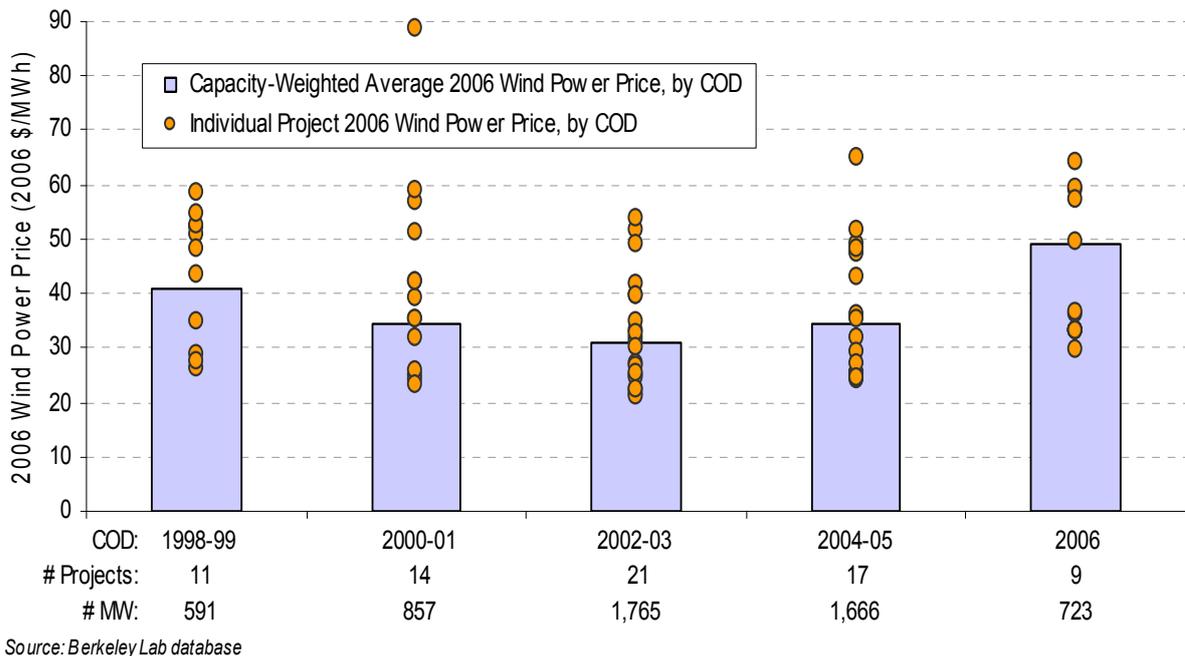
Studies have shown that in recent years, blade mass has been scaling at roughly an exponent of 2.3 instead of the expected 3, as shown by the WindPACT blade scaling study<sup>2</sup>. This WindPACT study shows how successive generations of blade design have moved off the cubic weight growth

curve to keep weight down as illustrated in Figure 5. If advanced research and development were to provide even better design methods, as well as new materials and manufacturing methods that allowed the entire turbine to scale as the diameter squared, then it would be possible to continue to innovate around this limit to size.

Land transportation constraints can also pose limiting factors to wind turbine growth for turbines installed on land. Cost-effective transportation can only be achieved by remaining within standard over-the-road trailer dimensions of 4.1 m high by 2.6 m wide. Rail transportation is even more dimensionally limited.

### 3 The Cost of Wind-Generated Electricity in the United States

The cost of wind-generated electricity has dropped dramatically since 1980, when the first commercial wind plants began operation in California. Figure 6 depicts price data for some more recent wind energy projects from public records. This chart shows that in 2006, the price paid for electricity generated in large wind plants was between 3 and 6.5 cents per kilowatt-hour (kWh) with an average near 5 cents per kWh (1cent/kWh = 10\$/MWh). These figures represent the electricity price as sold by a wind plant owner to the utility. The price includes the benefit of the federal production tax credit and any state incentives, as well as revenue from the sale of any renewable energy credits. Thus the true cost of the delivered electricity would be higher by approximately 1.9 cents per kWh, which is the value of the federal tax credit. Accounting for the tax credit, the unsubsidized cost for wind-generated electricity for projects completed in 2006 ranges from about 5 to 8½ cents per kWh.



Source: Berkeley Lab database

**Figure 6 Wind Energy Price by Commercial Operation Date Using 2006 Data (1).**

The reasons generally offered for the increasing price of wind-generated electricity after the long downward price trend of the past 25 years include:

- Turbine and component shortages due to the dramatic recent growth of the wind industry in the United States and Europe
- The weakening U.S. dollar relative to the Euro (because many major turbine components are imported from Europe) and relatively few wind turbine component manufacturers in the United States
- A significant rise in material costs such as steel and copper, as well as transportation fuels, over the past 3 years
- The on-again and off-again cycle of the wind energy production tax credit, which hinders investment in new turbine production facilities and encourages hurried and expensive production, transportation, and installation of projects when the tax credit is available.

Decreasing wind energy costs to below the 2003 level will require further research and development efforts and will be considered later.

#### **4 Potential Growth of Wind Energy in the United States**

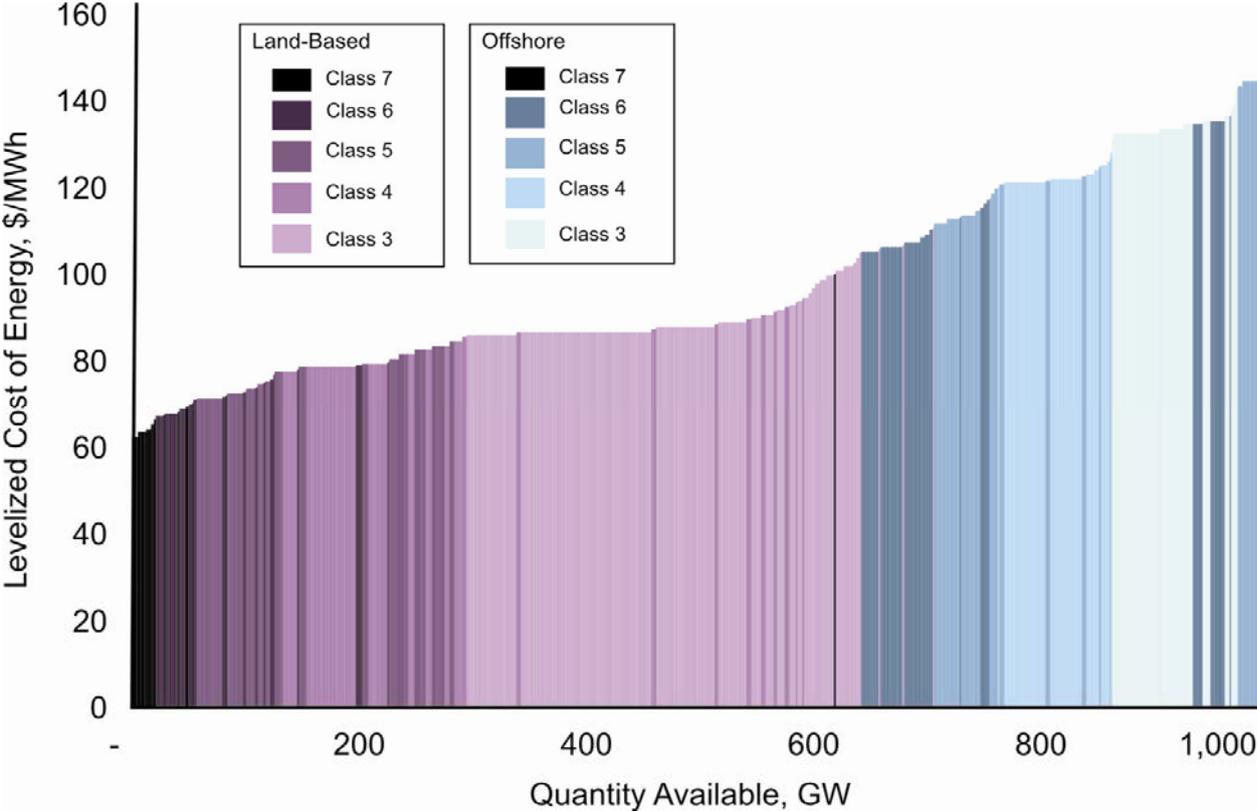
The vision of the wind industry in the United States and in Europe is to increase wind's fraction of the electrical energy mix to more than 20% within the next two decades. Recently, the U.S. Department of Energy in conjunction with American Wind Energy Association (AWEA), the National Renewable Energy Laboratory (NREL), Sandia National Laboratories, and Black & Veatch, undertook a study<sup>4</sup> to explore the possibility of producing 20% of the nation's electricity using wind energy. This investigation attempts to estimate all aspects of this scenario, including the wind resource assessment, materials and manufacturing resources, environmental and siting issues, transmission and system integration, and public policy. It should be noted that several states have Renewable Electricity Standards that mandate comparable levels of renewable energy be deployed within the next 20 years.

The Wind Energy Deployment System model<sup>3</sup> developed at NREL was used to estimate the consequences of producing 20% of the nation's electricity from wind technology by 2030. This generation capacity expansion model selects from electricity generation

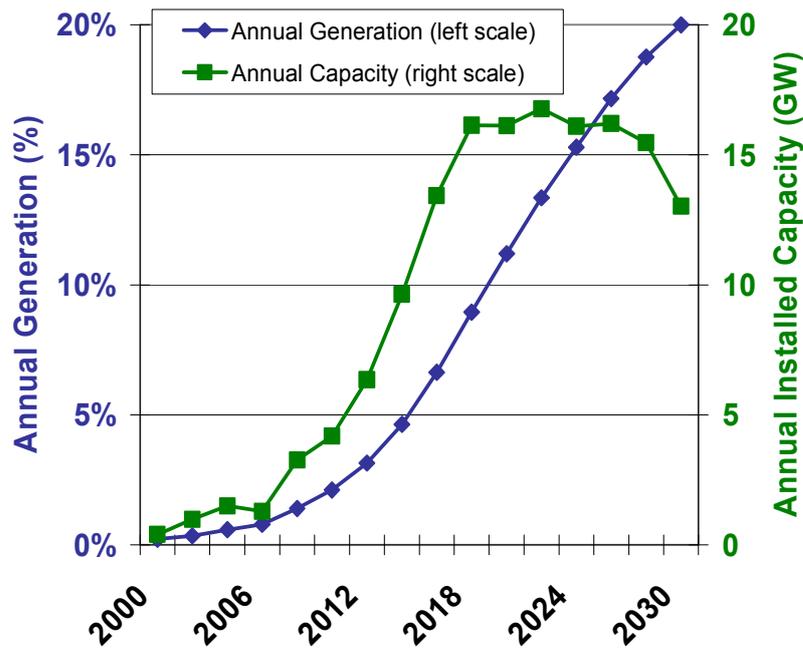
technologies that include pulverized coal plants, combined cycle natural gas plants, combustion turbine natural gas plants, nuclear plants, and wind technology to meet projected demand in future years. Technology cost and performance projections, as well as transmission operation and expansion costs, are assumed. This study demonstrates that producing 20% of the nation’s projected electricity demand in 2030 from wind technology is technically feasible, not cost-prohibitive, and provides benefits in the forms of carbon emission reductions, natural gas price reductions, and water savings.

reasonable cost if transmission expenditures are excluded. Considering some elements of the transmission required to access these resources, a supply curve that shows the relationship between wind power class and cost is shown in Figure 7, taken from reference (4). It includes the cost of accessing the current transmission system and shows that more than 600 GW of potential wind capacity is available for \$60 to \$100/MWh. The relatively flat supply curve for wind energy clearly shows an abundance of modestly priced wind energy is available in the United States, even with limited transmission access.

The United States possesses more than 8,000 gigawatts (GW) of wind resources that could be harnessed to produce electricity at



**FIGURE 7. Wind Energy Supply Curve for the 20% Wind Scenario Modeling**



**Figure 8. Prescribed annual wind generation and capacity additions**

Figure 8 shows the wind capacity expansion necessary to reach 20% electricity generation by 2030. This trajectory was designed to produce an aggressive annual growth rate that reached a sustainable level of manufacturing by accounting for both demand growth and the repowering of aging wind plants. Based on the assumptions used in this study, the wind industry would need to grow from an annual installation rate of 5 GW/year in 2007 to a sustained rate of about 15 GW/year by 2018, which is a threefold growth over the next decade.

The scenario assumes a modest improvement of wind technology over the 20-year modeling period. Wind turbine costs are assumed to decrease by 10% to 12% between 2010 and 2020, and wind turbine performance, or capacity factor, is assumed to increase by 15% from today's capacity factors of 35% by the year 2030. Although these increases do not appear to be particularly aggressive, they represent a significant technical challenge given the present situation where turbine costs are increasing with time not decreasing.

### 5 Offshore Wind Energy Potential

U.S. offshore wind energy resources are abundant, indigenous, and broadly dispersed among the most expensive and highly constrained electric load centers. The DOE Energy Information Administration shows that 28 of the 48 contiguous states with coastal boundaries use 78% of the nation's electricity. In the United States, approximately 10 offshore projects are being considered. Proposed locations span both state and federal waters and total more than 2,400 MW.

Offshore turbines being considered for deployment range from 3 MW to 5 MW in size and typically have three-bladed horizontal-axis upwind rotors that are nominally 80 m to 126 m in diameter. Tower heights offshore are lower than land-based turbines because wind shear profiles are less steep, tempering the energy capture gains sought with increased elevation. The foundations for offshore wind turbines differ substantially from land-based turbines. Current estimates indicate that the cost of energy from these offshore wind plants is more than 10 cents/kWh and that the operation and maintenance costs are also higher than for land-based turbines due to the difficulty of accessing turbines during storm conditions.

<b>Table 1: Areas of Potential Technology Improvement</b>			
<b>Technical Area</b>	<b>Potential Advances</b>	<b>Cost Increments (Best/Expected/Least, Percent)</b>	
		<b>Annual Energy Production</b>	<b>Turbine Capital Cost</b>
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 (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

**Footnote:** Since the 2002 baseline, there has already been a sizeable improvement in capacity factor, from just over 30% to almost 35%, while capital costs have increased due to large increases in commodity costs in conjunction with a drop in the value of the dollar (Ref. 1). Therefore, working from a 2006 baseline, we can expect a more modest increase in capacity factor, but the 10% capital cost reduction is still possible, although beginning from a higher 2007 starting point, because commodity prices are unlikely to drop back to 2002 levels.

The high cost of offshore wind energy and the need to develop a new regulatory process for permitting this unique technology has greatly slowed offshore wind development. Currently, there are no operating offshore wind plants in the United States. It is expected that during the next 5 years, one or more offshore wind farms will be deployed in the United States. They will be installed in shallow water and will supply electricity to nearby onshore utilities that serve large population centers. If they are successful, the technology will develop more rapidly. The much deeper water along the coastlines of the United States will not longer be able to use the concepts currently being installed in very shallow water.. However, the path toward deepwater floating systems must be supported by an extensive R&D program for at least a decade. For more information on the viability of offshore wind energy see reference (5).

## **6 Potential Future Turbine Technology Improvements**

The DOE Wind Energy Program has conducted cost studies under the WindPACT Project that identified a number of areas where technology advances would result in changes to the capital cost, annual energy production, reliability, operations and maintenance, and balance of station. Many of these potential improvements, summarized in Table 1, would have significant impacts on annual energy production and capital cost. Table 1 also includes the manufacturing learning-curve effect generated by several doublings of turbine manufacturing output over the coming years. The learning-curve effect on capital cost reduction is assumed to range from zero in a worst case scenario to the historic level in a best-case scenario, with the most likely outcome halfway in between. The probable scenario is a sizeable increase in capacity

factor with a modest drop in capital cost from the 2002 levels.

## 7 SUMMARY

Power production from wind technology has evolved very rapidly over the past decade. Capital costs have plummeted, reliability has improved, and efficiency has dramatically increased, resulting in robust commercial market product that is competitive with conventional power generation. Investments in R&D as well as the development of robust standard design criteria have helped to mitigate technology risk and attract market capital for development and deployment of large commercial wind plants. High-quality products are provided by every major turbine manufacturer, and complete wind generation plants are now being engineered to seamlessly interconnect with the grid infrastructure to provide utilities with dependable energy supply, free of the risks of future fuel price escalation inherent in conventional generation.

The cost-of-energy metric remains the principal technology indicator, incorporating the key elements of capital cost, efficiency, reliability, and durability. The unsubsidized cost of wind-generated electricity ranges from about 5 to 8.5 cents/kWh for projects completed in 2006 (1). No major technical breakthroughs in land-based technology are needed for a broad geographic penetration of wind power on the electric grid. Advancement requires a systems development and integration approach, reflecting the high level of engineering already incorporated into modern machines. No single component improvement in cost or efficiency can achieve significant cost reductions or dramatically improved performance. Capacity factor can be increased over time using enlarged rotors on taller towers. Market incentives are necessary to sustain near-term industry growth, but in the longer term, subsidies can probably be eliminated. In addition, with continued R&D, offshore wind energy has great potential to allow the United States to greatly expand its electrical energy supply.

## 8 References

1. Wisler, R.; Bolinger, M. (2007). *Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2006*, May 2007. National Renewable Energy Laboratory, Golden, CO. NREL Report No. TP-500-41435; DOE/GO-102007-2433. Available at [www.osti.gov/bridge](http://www.osti.gov/bridge).
2. Griffin, D. A. (2001). *WindPACT Turbine Design Scaling Studies Technical Area 1 -- Composite Blades for 80- to 120-Meter Rotor*. 44 pp.; National Renewable Energy Laboratory, Golden, CO. NREL Report No. SR-500-29492. Available at [www.nrel.gov/publications/](http://www.nrel.gov/publications/)
3. Short, W.; Blair, N.; Heimiller, D.; and Singh, V. (2003). *Modeling the Long-Term Market Penetration of Wind in the United States*, National Renewable Energy Laboratory, Golden, CO, NREL/CP-620-34469, 2003. Available at [www.nrel.gov/publications/](http://www.nrel.gov/publications/)
4. U.S. Department of Energy (2008). *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to the U.S. Electricity Supply*. National Renewable Energy Laboratory, Golden, CO. NREL Report No. NREL/SR-500-41869; DOE/GO-102008-2567. Available at [www.eere.energy.gov/windandhydro](http://www.eere.energy.gov/windandhydro)
5. Musial, W.; *Offshore Wind Electricity: A Viable Energy Option for Coastal USA*, *Marine Technology Society Journal*, Volume 41(3), Fall 2007; pp. 32-43; National Renewable Energy Laboratory, Golden, CO. NREL Report NO. NREL/JA-500-41338. Available at [www.nrel.gov/publications/](http://www.nrel.gov/publications/)

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

**PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> October 2008		<b>2. REPORT TYPE</b> Conference Paper		<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b> Future of Wind Energy Technology in the United States				<b>5a. CONTRACT NUMBER</b> DE-AC36-08-GO28308	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b> R. Thresher, M. Robinson, and P. Veers				<b>5d. PROJECT NUMBER</b> NREL/CP-500-43412	
				<b>5e. TASK NUMBER</b> WER8.2006	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> NREL/CP-500-43412	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> NREL	
				<b>11. SPONSORING/MONITORING AGENCY REPORT NUMBER</b>	
<b>12. DISTRIBUTION AVAILABILITY STATEMENT</b> National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT (Maximum 200 Words)</b> This paper describes the status of wind energy in the United States as of 2007, its cost, the potential for growth, offshore wind energy development, and the potential future wind energy technology improvements.					
<b>15. SUBJECT TERMS</b> wind energy; wind turbines; offshore wind energy development					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b> UL	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			<b>19b. TELEPHONE NUMBER (Include area code)</b>

Standard Form 298 (Rev. 8/98)  
Prescribed by ANSI Std. Z39.18