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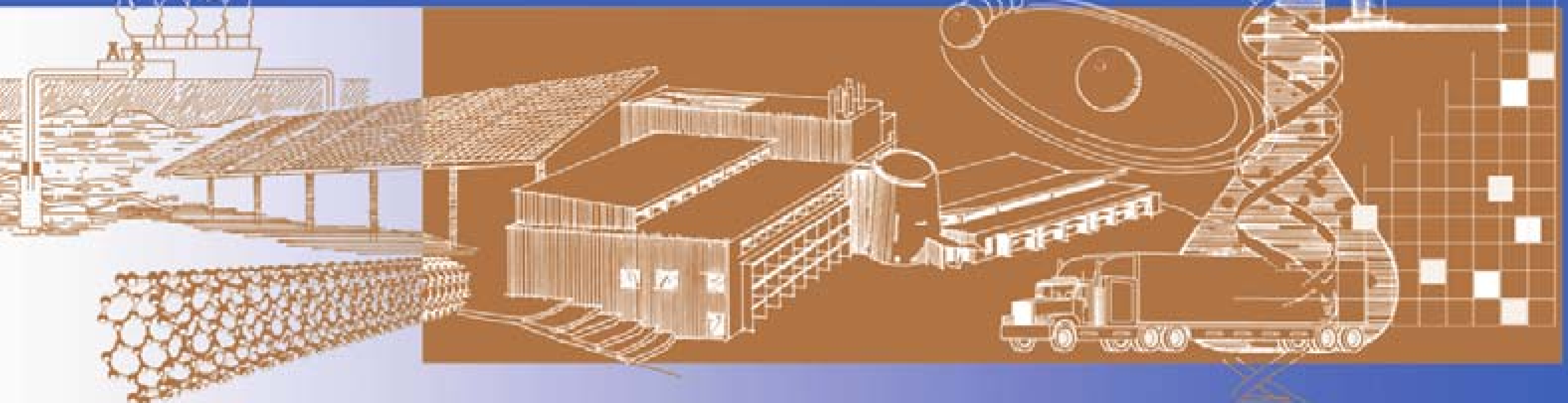

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Wind Energy Technology: Current Status and R&D Future

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Abstract. Wind energy is one of the fastest-growing electrical energy sources in the United States. The United States installed over 5,200 MW in 2007 and experts are forecasting for as much to be installed in 2008. The United States cumulative installed capacity as of Dec. 31, 2007, was 16, 596 MW. Wind turbines have evolved rapidly over the past 20 years and the turbines have grown in size from 100 kW in the early 1980s to over 2.5 MW today. The evolution of wind technology is expected to continue over the next two decades resulting in a continued improvement in reliability and energy capture with a modest decrease in cost. The development of new and innovative rotors, drive systems, towers, and controls is expected to enable this continued improvement in the cost effectiveness of wind technology. Wind energy can supply 20% of the United States' electricity needs by 2030 and will be a significant contributor to the world's electricity supply.

INTRODUCTION TO WIND ENERGY

Wind energy is one of the fastest-growing electrical energy sources in the United States. The United States installed over 5,200 MW in 2007, and experts are forecasting for as much to be installed in 2008. The United States cumulative installed

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capacity as of Dec. 31, 2007, was 16,596 MW. The state distribution of wind capacity is illustrated in Figure 1.

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

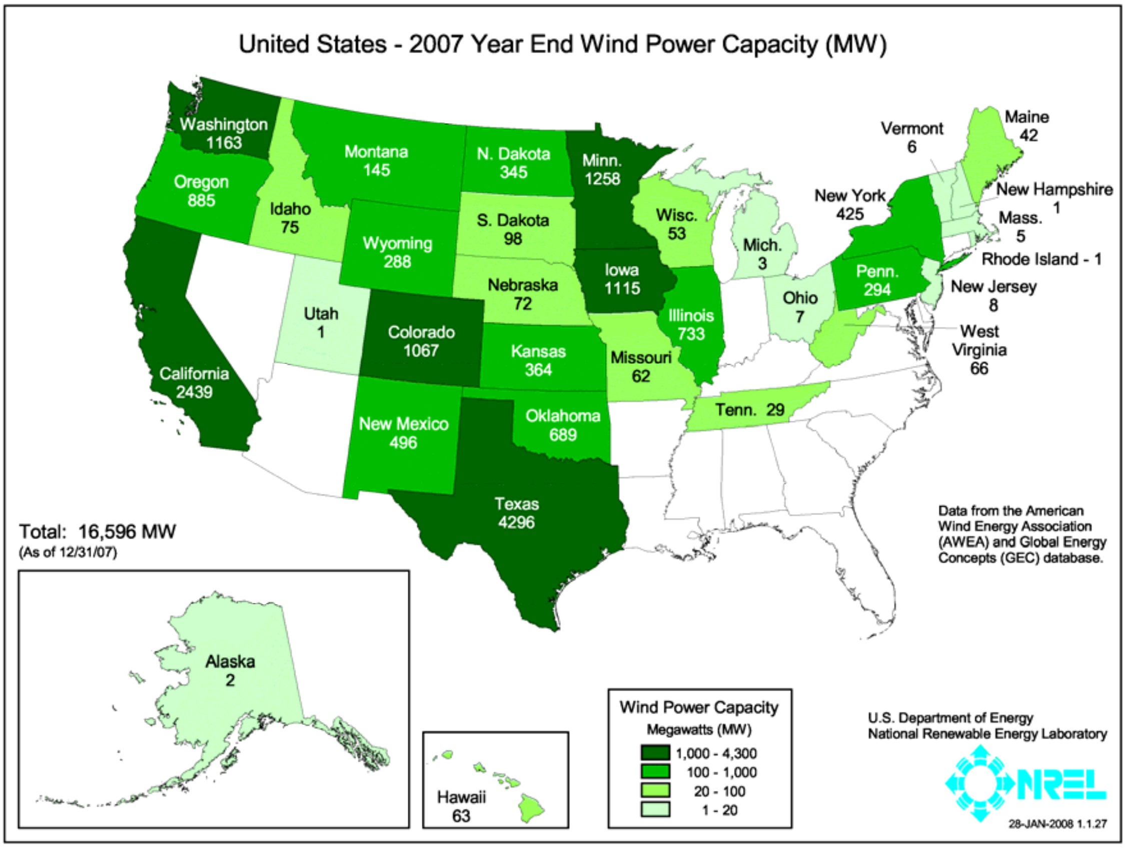

FIGURE 1. Installed wind capacity in the United States as of Dec. 31, 2007.

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.

Modern wind turbines deployed throughout the world today have three-bladed rotors with diameters of 70 to 80 meters mounted atop 60- to 80-m towers as shown in Figure 3. The typical turbine installed in the United States in 2007 can produce about 1.5 MW of electrical power. The turbine power output is controlled by rotating the blades on their long axis to change the angle of attack with respect to the relative wind as the blades spin about the rotor hub, which is referred to as "controlling the blade pitch". The turbine is pointed into the wind by rotating the nacelle about the tower, which is called "yaw control". Almost all modern turbines operate with the rotor positioned on the windward side of the tower, which is referred to as an "upwind rotor”. Wind sensors on the nacelle tell the yaw controller where to point the turbine, and when combined with sensors on the generator and drive train, tell the blade pitch controller to regulate the power output and rotor speed to prevent overloading structural components. A turbine will generally start producing power in winds of about 5.4 m/s (12 mph) and reach maximum power output at about 12.5 m/s to 13.4 m/s (28 to 30 mph). The turbine will “feather the blades” (pitch them to stop power production and rotation) at about 26.8m/s (60 mph).

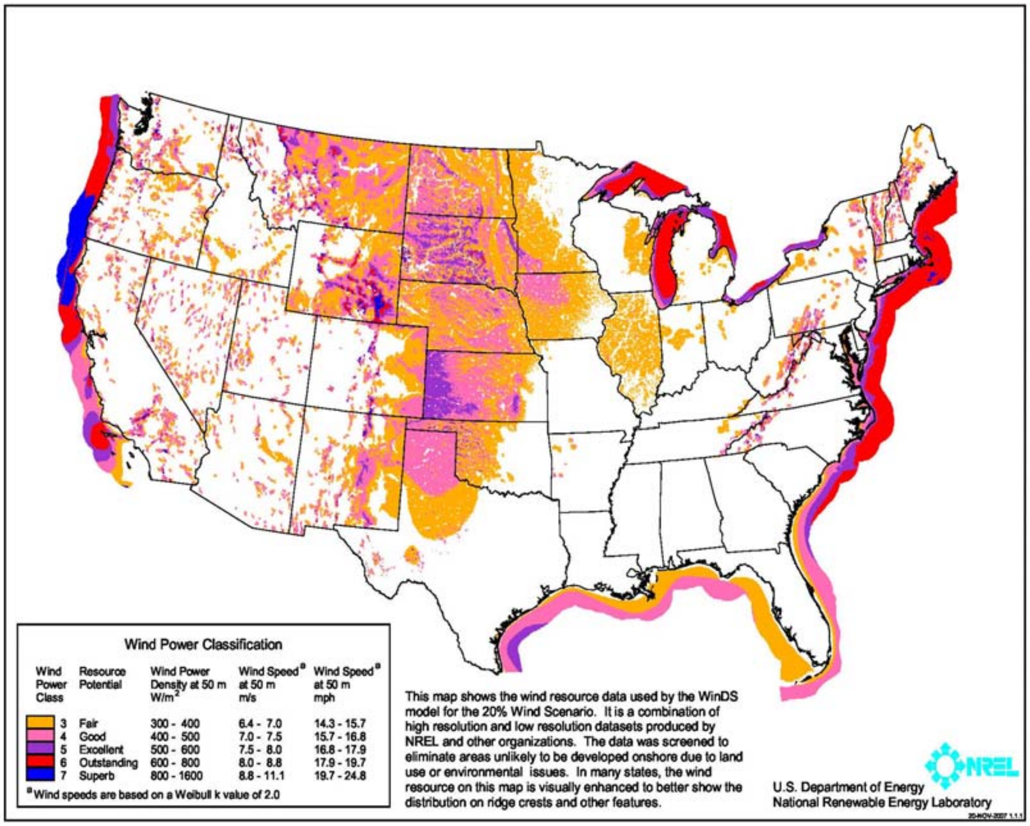

FIGURE 2. The wind resource potential at 50m on land and offshore.

The amount of energy in the wind available for extraction by the turbine increases with the cube of wind speed; thus a 10% increase in wind speed means a 33% increase in available energy. However, a turbine can only capture a portion of this cubic increase in energy 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 (as will be described later).

The height and the size of wind turbines have increased to capture the more energetic winds at higher elevations. For land-based turbines, size is not expected to grow as dramatically in the future as it has in the past. Many turbine designers don’t expect land-based turbines to become much larger than about 100 meters in diameter, with corresponding power outputs of about 3 to 5 MW. Larger sizes are physically possible; however, the logistical constraints of transporting the components over the highway and obtaining cranes large enough to lift the components are potential barriers.

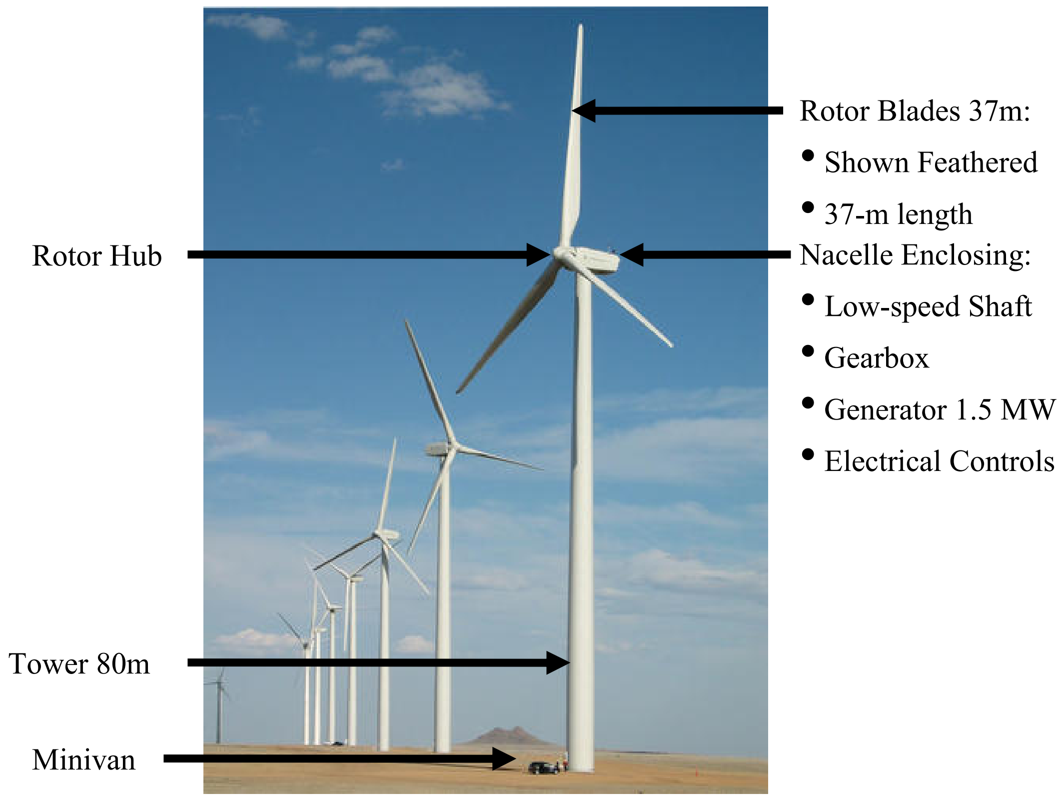

FIGURE 3. A modern 1.5 MW wind turbine installed at a wind farm (photo by Mark Rumsey, Sandia National Laboratories).

THE NATIONAL POTENTIAL FOR WIND ENERGY

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

The Wind Energy Deployment System model[1] developed at NREL was used to estimate some of the important consequences associated with 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, and water savings. The reader interested in additional information on 20% Wind Energy by 2030 is referred to U. S. Department of Energy Report[2].

The United States possesses ample wind resources, technically more than 8,000 GW, that could be harnessed to produce electricity at 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 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.

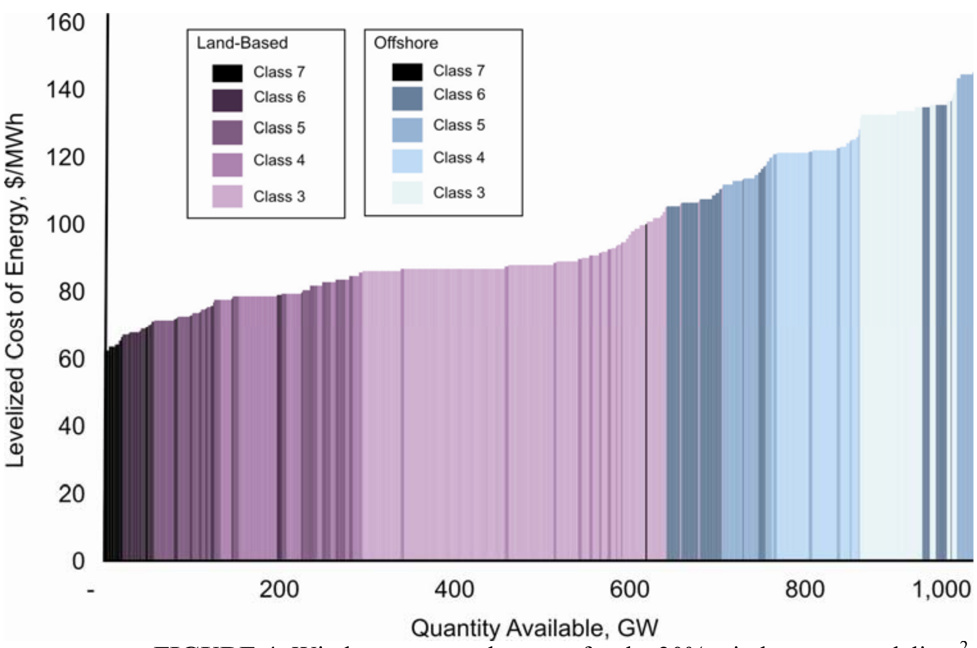

FIGURE 4. Wind energy supply curve for the 20% wind energy modeling.[2]

Figure 5 shows the resulting 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/yr in 2007 to a sustained rate of about 15 GW/yr by 2018, which is a threefold growth over the next decade.

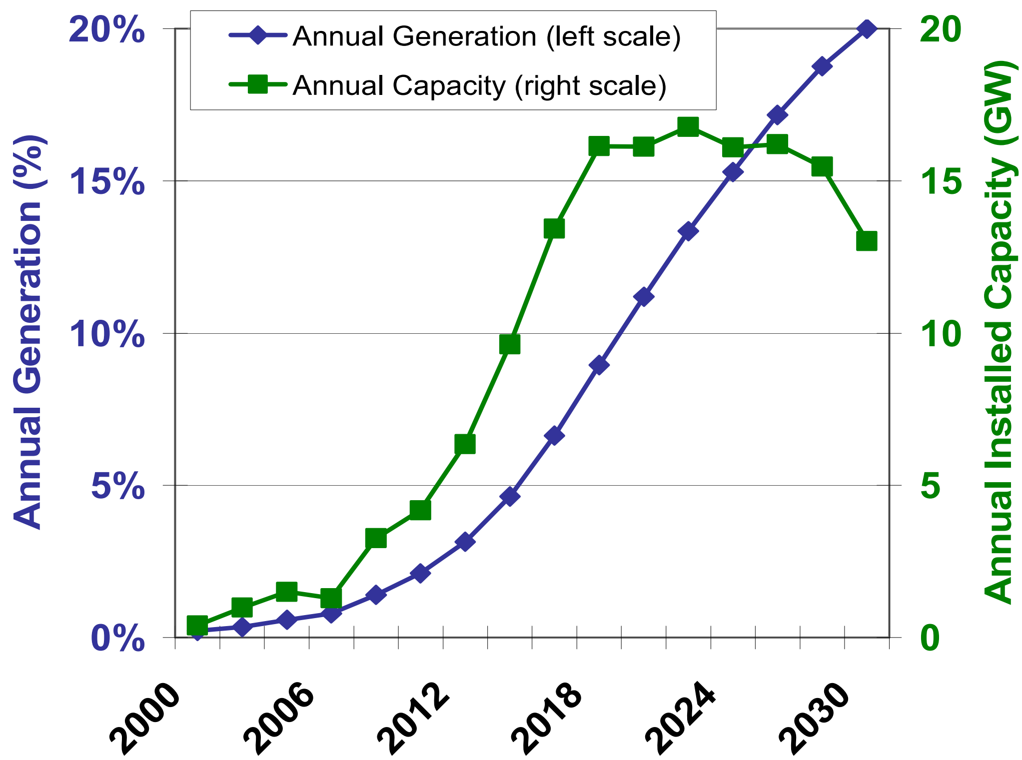

FIGURE 5. Prescribed annual wind energy generation and corresponding annual wind capacity additions through 2030.

The scenario does assume 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 to 50%, up from today's capacity factors of 35%, by the year 2030. Although these increases do not appear to be particularly aggressive, they are quite challenging and represent a significant technical challenge given the present situation where turbine costs are increasing with time.

THE HISTORY OF WIND TECHNOLOGY DEVELOPMENT

Until the early 1970s, wind energy filled a small niche market providing mechanical power for grinding grain and pumping water. With the exception of a small number of battery chargers and the rare experiments with larger electricity-producing machines, the windmill of 1850, or even 1950, differed little from the primitive devices from which they were derived. But the latter half of the 20th century saw spectacular changes in the technology. Blades that had once been made of sail or sheet metal progressed through wood to advanced fiberglass composites. The DC alternator gave way to the induction generator that was grid synchronized. From mechanical cams and linkages that feathered or furled a machine, designs moved to high-speed digital controls. Airfoils are now tested in wind tunnels and are designed for insensitivity to surface roughness and dirt. Current knowledge of aeroelastic loads and the ability to incorporate this knowledge into detailed numerical models and structural dynamics codes make the machine of today more robust, but much less expensive than those of a decade ago.

Turbine Size

Over the past 20 years, average wind turbine ratings have grown almost linearly (Figure 6) with current commercial machines rated at 1.5 MW. Each group of wind turbine designers has predicted that their machines are 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, 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 has increased over time, as documented by Wiser and Bolinger[3]. However, there are constraints to this continued growth to larger sizes as in general it costs more to build a larger turbine.

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 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[4]. The 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 7. 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.

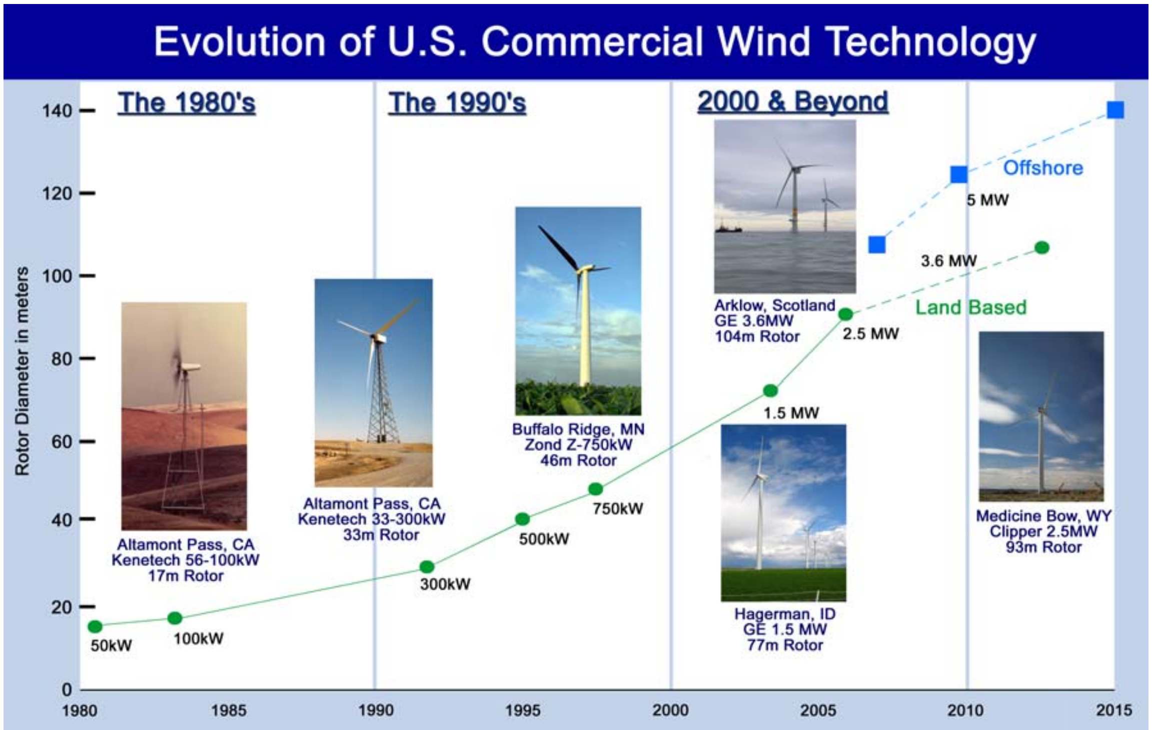

FIGURE 6. The development path and size growth of wind turbines.

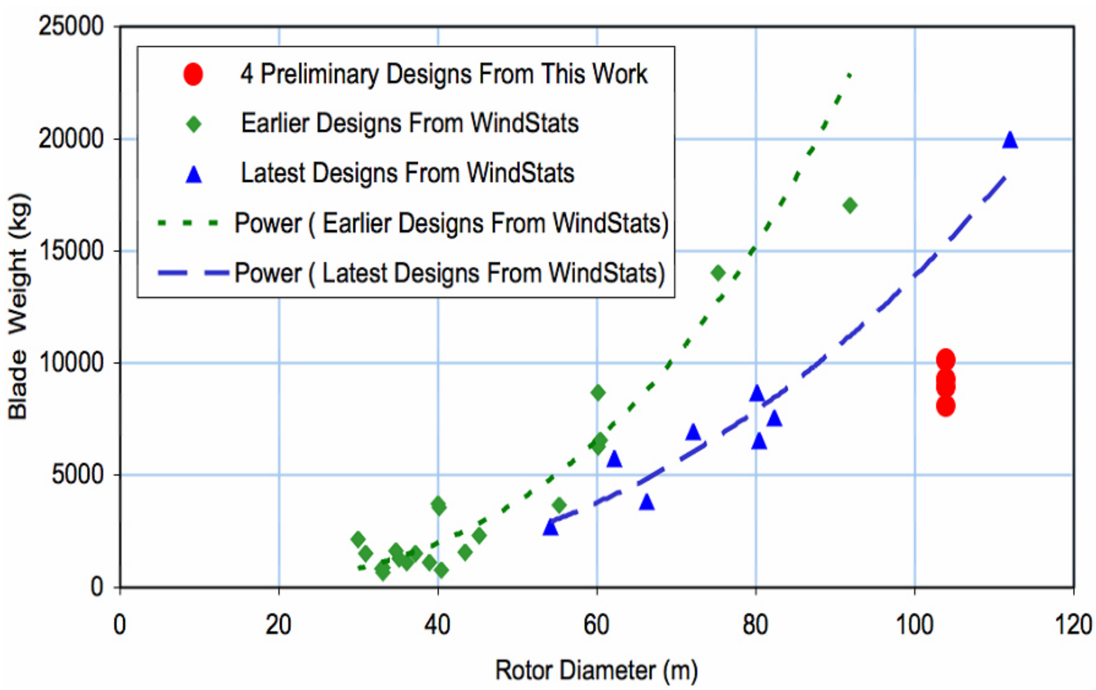

FIGURE 7. WindPACT[4] study results indicating the lowering of growth in blade weight due to the introduction of new technology.

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, frequently eliminating that option.

Unfortunately, other constraints limit the practical size of wind turbines. 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 becomes fairly limited. Other limiting factors are that cranes with large lifting capacities are difficult to transport, require large crews, and therefore have high operation, mobilization, and de-mobilization costs.

The Rotor

As wind turbines grow in size, so do their blades— from about 8m in 1980 to more than 40m for many land-based commercial systems. Improved blade designs have enabled the weight growth to be kept to a much lower rate than simple geometric scaling, as already described. Today's blade designs are subjected to rigorous evaluation using the latest computer analysis tools so that excess weight can be removed. Designers are also starting to work with lighter and stronger carbon fiber in highly stressed locations to stiffen the blade and improve fatigue resistance while reducing blade weight. However, carbon fiber must be used judiciously because the cost is about 10 times that of fiberglass.

Figure 8 shows the power curve for a typical modern turbine and illustrates the different control regions for the turbine. Typically, a turbine will cut-in and begin to produce power at a wind speed of about 5.4 m/s (12 mph). It will reach its rated power at about 12.5 m/s to 13.4 m/s (28 to 30 mph), where the pitch control system begins to limit power output and prevent overloading the generator and drive train. At around 26.8 m/s (60 mph), the control system pitches the blades to stop rotation (which is referred to as feathering the blades) to prevent overloads and damage to the turbine's components.

All of the energy present in a stream of moving air cannot be extracted; some air must remain in motion after extraction or no new, more energetic air can enter the device. Building a brick 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 solution for the optimal blockage is generally attributed to the German Physicist Albert Betz and is called the Betz limit. At best, a device can extract a theoretically maximum 59% of the energy in a stream with the same area as the working area of the device.

The aerodynamic performance of a modern wind turbine has improved dramatically over the past 20 years. The rotor system can be expected to capture about 80% of the theoretically possible energy in the flow stream. This has been made possible through the design of custom airfoils for wind turbines. In fact, it is now commonplace for turbine manufacturers to have special airfoil designs for each individual turbine design. These special airfoils attempt to optimize low-speed wind aerodynamic efficiency and limit aerodynamic loads in high winds. These new airfoil designs also attempt to minimize sensitivity to blade fouling, due to dirt and bugs that accumulate on the leading edge and can greatly reduce efficiency. Although rotor design methods have improved significantly, there is still room for improvement.

Controls

Today's controllers integrate the 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 realized. Today, most turbines operate at variable-speed, and the control system regulates the rotor speed to obtain peak efficiency in fluctuating winds by continuously updating the rotor speed and generator loading to maximize power and reduce drive train transient torque loads. Operating variable speed requires the use of power converters to make the generated power match the grid frequency. The power converter also enables turbines to deliver fault ride through protection, voltage control, and dynamic reactive power support to the grid.

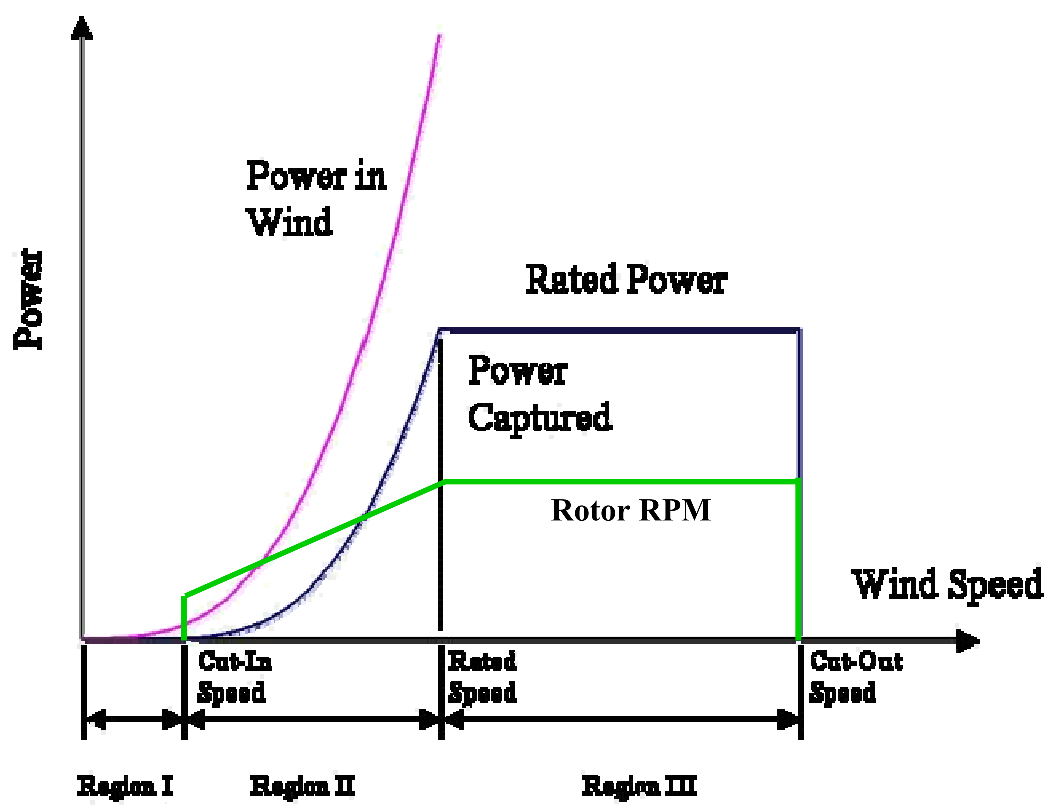

FIGURE 8. A typical power output versus wind speed curve.

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The Drive Train (Gearbox, Generator, and Power Converter)

Wind generation of electricity places an unusual set of requirements on electrical systems. Most applications for electrical drives are aimed at using electricity to produce torque, rather than 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. Traditional electrical machines and power electronics disappoint because in most motor applications, there is power to spare and efficiency is less important in this low-power region. For wind systems, it is not critical for the generation system to be efficient in above-rated winds where the rotor lets energy flow through to keep the power down to the rated level. Therefore, wind systems can afford inefficiencies at high power while they require maximum efficiency at low power—just the opposite of almost all other electrical applications in existence.

Converting torque to electrical power has historically been achieved 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 due to their fault-ride-through and other grid-support capacities.

Due to fleet-wide gearbox maintenance issues and related failures with some past designs, it has become standard practice to perform extensive dynamometer testing of new gearbox configurations to prove durability and reliability prior to introducing them into serial production. The long-term reliability of the current generation of megawatt-scale drive trains has not yet been fully verified with long-term real world operating experience. There is a broad consensus that wind turbine drive train technology will evolve significantly in the next several years.

The Tower

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

Balance of Station

The balance of the wind farm station consists of turbine foundations, the wind farm electrical collection system, wind farm power conditioning equipment, supervisory control and data acquisition systems, access and service roads, maintenance buildings, service equipment, and engineering permits. The combination contributes about 20% to the installed cost of a wind farm.

Cost, Operations, Reliability, and Availability

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 \$0.5 to \$0.085/kWh for projects completed in 2006[3]. Operations and maintenance (O&M) costs have dropped significantly since the 1980s due to improved designs and increased quality. Reference 3 presents data that show O&M expenses are a significant portion of the total system cost of energy. O&M costs are reported to be as high as \$0.3 to \$0.5/kWh for wind farms with 1980s technology, whereas the latest generation of turbines has reported O&M costs below \$0.1/kWh. Availability, defined as the fraction of time during which the equipment is ready to operate, is now over 95% and often reported to exceed 98%.

WIND TECHNOLOGIES OF THE FUTURE

The European Wind Energy Technology Platform[5] envisions that "in 2030, wind energy will be a major modern energy source, reliable and cost competitive in terms of cost per kWh." In addition, they foresee that wind energy will contribute 21% to 28% of the European Union (EU) electricity demand, which is similar to the scenario described previously for the United States. The European Wind Energy Technology Platform describes a long series of research and development improvements that will be necessary to make wind cost competitive by 2030. The reader interested in this challenging multi-disciplinary research program is referred to reference 5. There is no "big technology breakthrough" envisioned for wind technology in the United States or in Europe. However, many evolutionary steps executed with technical skill can cumulatively bring about a 30% to 40% improvement in the cost effectiveness of wind technology over the next two decades.

Advanced Rotors

As turbines grow larger and larger, rotors must improve their ability to handle large dynamic loads with increased structural efficiency to avoid the costly cubic weight growth described previously. Several approaches are being developed and tested to help alleviate these load levels or create load-resistant designs. High strength-to-weight ratio carbon fibers are now being incorporated into the high-stress areas of wind turbine blades, which will reduce overall blade weight.

Another approach to reducing cost involves developing new blade airfoil shapes that are much thicker where the blade needs it most, producing inherently better structural properties. In general, thin flat structures like airfoils are very inefficient at carrying structural loads. The trick is to make a thick and structurally efficient blade airfoil shape that doesn't give up much in aerodynamic performance. Figure 9 illustrates such an airfoil shape, which is used near the root of the blade where the flatwise bending loads are the highest, and better structure pays the highest return, but where aerodynamic performance is less important. For additional insight into the aerodynamic design of this type of airfoil the interested reader is referred to the work of Berg and Zayas[6]. An additional benefit is that blades with a shorter chord at the root are more easily transported over the highway due to the width and height restrictions described previously.

Another approach to increasing blade length while restraining the weight and cost growth is to reduce the fatigue loading on the blade. There can be a big payoff in this approach because the approximate rule of thumb for fiberglass blades is that a 10% reduction in cyclic stress can provide about an order of magnitude increase in fatigue life. Blade fatigue loads can be reduced by controlling the blade's aerodynamic response to turbulent wind inputs by actively flying the blade using the pitch control system of the turbine. This approach is being explored using modern state space control strategies so that future turbines can take advantage of this innovation. The interested reader is referred to Wright and Fingersh[7] for a research study on advanced controls and plans for future work.

FIGURE 9. A flat-back thick airfoil shape with high structural efficiency and easier highway transport.

An elegant concept is to build passive means of reducing loads directly into the blade structure. By carefully tailoring the structural properties of the blade using the unique attributes of composite materials, the blade can be built in a way that couples the bending deformation of the blade to twisting deformation. This is referred to as flap-pitch, or bend-twist, coupling and allows the outer portion of the blade to twist as it bends Figure 9. This is accomplished by designing the internal structure of the blade, or orienting the fiberglass and carbon plies within the composite layups, in such a way as to make the blade twist as it is bent. This twisting changes the angle of attack over much of the blade. If properly designed, this change in angle of attack will reduce the lift as wind gusts begin to load the blade and therefore passively reduce the fatigue loads. Another approach to achieving pitch-flap coupling is to build the blade in a curved shape so that the aerodynamic load fluctuations apply a twisting movement to the blade, which will vary the angle of attack. The reader interested in more information on the performance and design of bend-twist blades is referred to references 8 and 9. These new blade designs are complex and must be developed, tested, and optimized so as not to adversely impact energy production or result in unstable vibrations.

Concepts such as on-site manufacturing and segmented blades are also being explored to help reduce transportation costs. It may 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 at the wind farm site.

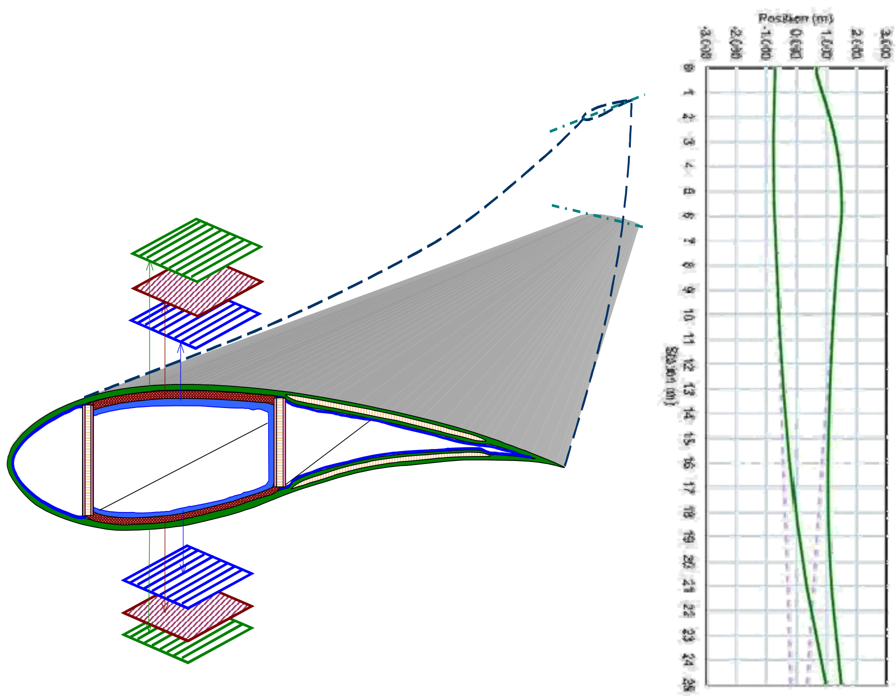

FIGURE 10. A twist–flap coupled blade design to alleviate fatigue loads (on the left with material coupling and on the right with a curved blade).

Advanced Drive Trains

Several unique designs are under development to reduce drive train weight and cost while improving reliability. These have been explored in design studies under the WindPACT project described in the reference 10 report. One approach for improving reliability is to build a direct drive generator that eliminates the complexity of the gearbox. The tradeoff is that the slowly rotating generator must have a high pole count and is large in diameter. Depending on the design, the generator can be in the range of 4 to 10 m in diameter and can be quite heavy.

The decrease in cost and increase in availability of rare earth permanent magnets is expected to significantly affect the size and cost of future permanent-magnet generator designs. Permanent-magnet designs tend to be quite compact and lightweight and reduce electrical losses in the windings. A 1.5 MW direct-drive generator using rare earth permanent magnets has been studied and a prototype has been built. This design uses 56 poles and is only 4 m in diameter, versus the 10 m for a wound rotor design[11]. This machine has undergone testing at NREL's National Wind Technology Center.

A hybrid of the direct-drive approach that offers promise for future large-scale designs is the single-stage drive using a low-speed generator. This allows the use of a low-speed generator that is significantly smaller than a comparable direct-drive design. The WindPACT drive train project has developed a prototype for such a drive train. This design uses a single-stage planetary drive operating at a gearbox ratio of 9.16:1. This gearbox drives a 190 RPM, 72-pole, permanent-magnet generator. This approach, which reduces the diameter of a 1.5 MW generator to 2 m[10], was fabricated and was also tested on the dynamometer at NREL's National Wind Technology Center.

Another approach that offers promise for reduced size, weight, and cost is the distributed drive train. This concept is based on splitting the drive path from the rotor to drive several parallel generators. Studies have shown that by distributing the rotor torque on the bull gear over a number of parallel secondary pinions, a significant size and weight reduction is achieved. In 2006, Clipper Windpower developed a 2.5 MW prototype (Figure 11), which incorporates this approach and is currently in the new 2.5 MW Liberty turbine. Here again, the development of new technology for incorporation into a production turbine takes significant R&D resources and a number of years to insure a reliable production product.

Innovative Towers

The cost impact of extremely large cranes and the transport premiums for large tower sections and blades is driving the exploration of novel tower design approaches. Several concepts are under development or being proposed that would eliminate the need for cranes for very high, heavy lifts. One concept is the telescoping or self-erecting tower. Other self-erecting designs include lifting dollies or tower-climbing cranes that use tower-mounted tracks to lift the nacelle and rotor to the top of the tower. Further information on innovative towers can be found in reference 12.

FIGURE 11. Clipper Windpower's distributed drive train.

Summary of Potential Future Turbine Technology Improvements

The DOE Wind 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 the 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 most likely scenario is a sizeable increase in capacity factor with a modest drop in capital cost (over the 2002 levels of each).

Table 1: Areas of Potential Technology Improvement			
Technical Area	**Potential Advances**	**Cost Increments (Best/Expected/Least, Percent)**	
		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 (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

TABLE 1. 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 dollar3.. 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.

OFFSHORE WIND ENERGY

U.S. Offshore wind energy resources are abundant, indigenous, and broadly dispersed among the most expensive and highly constrained electric load centers. The U.S. Department of Energy's Energy Information Agency shows that the 28 states in the contiguous 48 states with a coastal boundary use 78% of the nation's electricity.

Nineteen offshore wind projects now operate in Europe with an installed capacity of 900 MW. All installations have been in water depths less than 22 m. Although some projects have been hampered by construction overruns and higher-than-expected maintenance, projections show strong offshore growth in many EU markets. 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.

The current shallow-water offshore wind turbine is basically an upgraded version of the standard land-based turbine with some system redesigns to account for ocean conditions. These modifications include structural upgrades to the tower to address the added loading from waves, pressurized nacelles, and environmental controls to prevent corrosive sea air from degrading critical drive train and electrical components, and personnel access platforms to facilitate maintenance and provide emergency shelter. To minimize expensive servicing, offshore turbines may be equipped with enhanced condition monitoring systems, automatic bearing lubrication systems, on-board service cranes, and oil temperature regulation systems, all of which exceed the standard for land-based designs.

Today's offshore turbines range from 3 MW to 5 MW in size and typically have three-blades, operate with a horizontal-axis upwind rotor, and are nominally 80 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 offshore foundations differ substantially from land-based turbines.

The baseline offshore technology is deployed in arrays using monopiles at water depths of about 20 m. Monopiles are large steel tubes with a wall thickness of up to 60 mm and a diameter of 6 m. The embedment depth will vary with soil type, but a typical North Sea installation will require a pile that is embedded 25 to 30 m below the mud line that extends above the surface to a transition piece with a leveled and grouted flange on which the tower is fastened. Mobilization of the infrastructure and logistical support for a large offshore wind farm is a significant portion of the system cost.

Current estimates indicate that the cost of energy from offshore wind plants is above \$0.10/kWh and that the O&M costs are also higher than for land-based turbines due to the difficulty of accessing turbines during storm conditions.

There are three logical pathways (Figure 12) representing progressive levels of complexity and development that will lead to cost reductions and greater offshore deployment potential. The first path is to lower costs and remove deployment barriers for shallow water technology in water depths of 0 to 30 meters. The second path is transitional depth technology, which is needed for depths where current technology no longer works. This technology deals mostly with substructures that are adapted from existing offshore oil and gas practices. Transitional depths are defined to be 30 to 60 meters. The third path is to develop technology for deep water, defined by depths between 60 and 900 meters. This technology will probably use floating systems, which require more R&D to design turbines that are lighter and can survive the added tower motion on anchored, buoyant platforms.

The ultimate vision for offshore wind energy is that it would open up major areas of the outer continental shelf to wind energy development. This would require the use of deep water floating platforms that could be mass produced and assembled in dry docks and then floated out and anchored without extensive assembly at sea. Deep water technology also avoids the need for long-distance transmission because the wind farms can be located much closer to load centers.

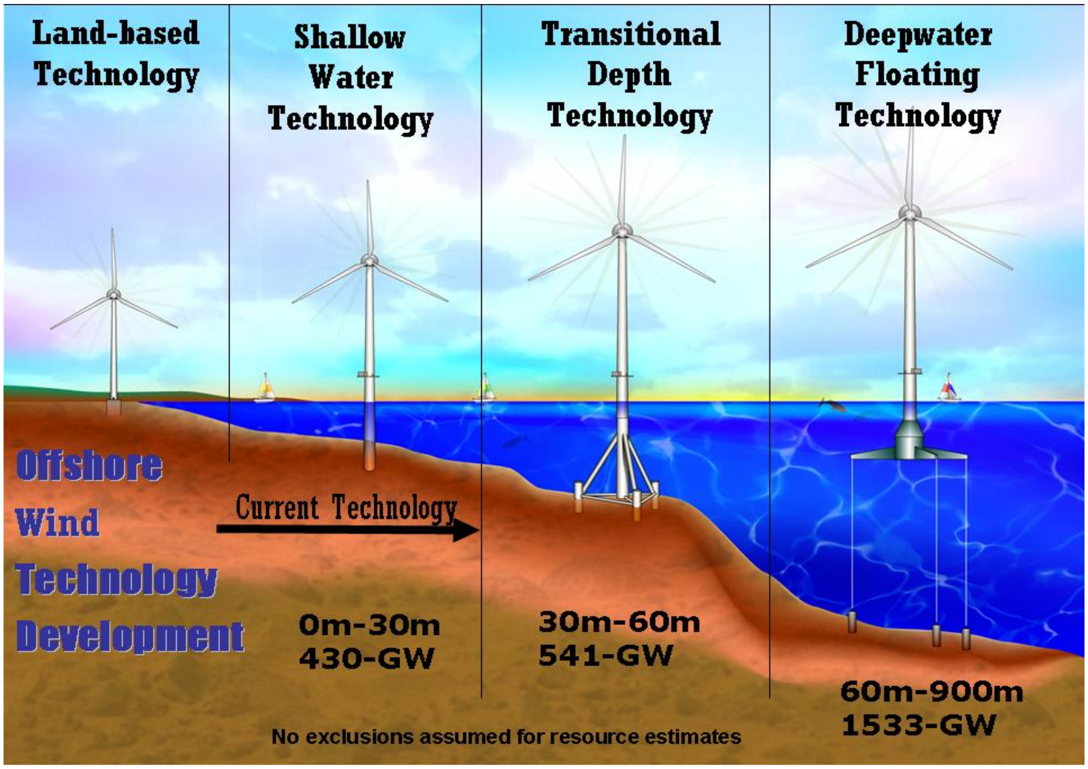

FIGURE 12. Offshore development pathways.

New offshore technologies will be required to grow wind turbines into 5 to 10 MW sizes or greater. These technologies may include lightweight composite materials and composite manufacturing, lightweight drive train, modular pole direct drive generators, hybrid space frame towers, and large gearbox and bearing designs that are tolerant of slower speeds and large scale. The cost of control systems and sensors that monitor and diagnose turbine status and health will not grow substantially as turbine size increases, and high reliability will be essential due to the limited access during severe storm conditions, which can persist for extended periods.

It is expected that over the next five years, one or more offshore wind farms will be deployed in the United States. They will be installed in shallow water and supply electricity to nearby onshore utilities serving large population centers. If they are successful, the technology will develop more rapidly and the move to deep water systems will progress at a more rapid rate. However, the path toward floating systems must be supported by an extensive R&D program over a decade or more. Further information on the viability of offshore wind energy is provided in reference 13.

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. Complete wind generation plants are now being engineered to seamlessly interconnect with the grid infrastructure to provide utilities with 0a dependable energy supply, free of the risks of future fuel price escalation inherent in conventional generation.

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 will remain necessary to sustain the industry growth in the near term, 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 the contribution from wind in its electrical energy supply.

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