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WIND ENERGY AS A SIGNIFICANT SOURCE OF ELECTRICITY FOR THE UNITED STATES

R. Gerald Nix

ABSTRACT
This paper discusses wind energy and its potential to significantly impact the generation of electricity within the United States. The principles and the equipment used to convert wind energy to electricity are described, as is the status of current technology. Markets and production projections are given. There is discussion of the advances required to reduce the selling cost of electricity generated from the wind from today's price of about $0.05 per kilowatt-hour to full cost-competitiveness with gas- and coal-based electricity.

INTRODUCTION

Wind energy has the potential to produce a significant fraction of the electricity used in the United States. The wind is a proven energy source with no insolvable technical constraints. The technology is market ready, although cost improvements are required for wind-generated electricity to be fully competitive with coal- and natural-gas-fired baseload electricity. Utility-size wind plants currently produce electricity for about $0.05 per kilowatt-hour in a location with a 13 mile-per-hour annual wind speed measured at 10 m. This paper describes the technology and the research and development activities that will significantly reduce the cost of wind-generated electricity.

THE WIND RESOURCE AND ITS POTENTIAL FOR ELECTRICITY GENERATION

Wind energy results from air in motion, with the motive force being thermal gradients produced from uneven solar heating of the earth's surface. The scale of the motion can be very large, and the local energy content of the wind is dependent upon the topography and other structures that can affect the flow. In most locales, the wind is an intermittent energy source.

Because the energy in the wind is kinetic energy, the power density within the wind is proportional to the wind speed raised to the third power. Wind is normally categorized as one of seven classes, according to power density: Class 1 is the lowest and Class 7 is the highest [1]. For utility applications, Class 4 or higher energy classes are usually required, with an average power density in the range of 320–400 W/m^2, which corresponds to a moderate speed of about 5.8 m/s (13 mph). Researchers estimate that there is enough wind potential in the United States to displace at least 45 quads of primary energy used to generate electricity [1]. This is based on Class 4 winds or greater and the judicious use of land. For reference, the United States used about 32.6 quads of primary energy to generate electricity in 1995 [2]. A quad is a quadrillion (10^{15}) Btu, which is equivalent to the energy in 167 million barrels of oil.

Figure 1 shows a wind resource map (annual average) for the contiguous United States. Although almost all of the currently installed wind electric generation capacity is in California, the major wind energy resource is virtually untapped in the Great Plains region. About 90% of the wind energy resource in the contiguous United States is contained in 11 states in the Great Plains. This area ranges from Texas north to Canada, and east from Colorado into Iowa. Expansion of wind energy into this high-resource area is just beginning, with promise of significant future implementation. A good description of the wind resource is found in an article by Schwartz [3].

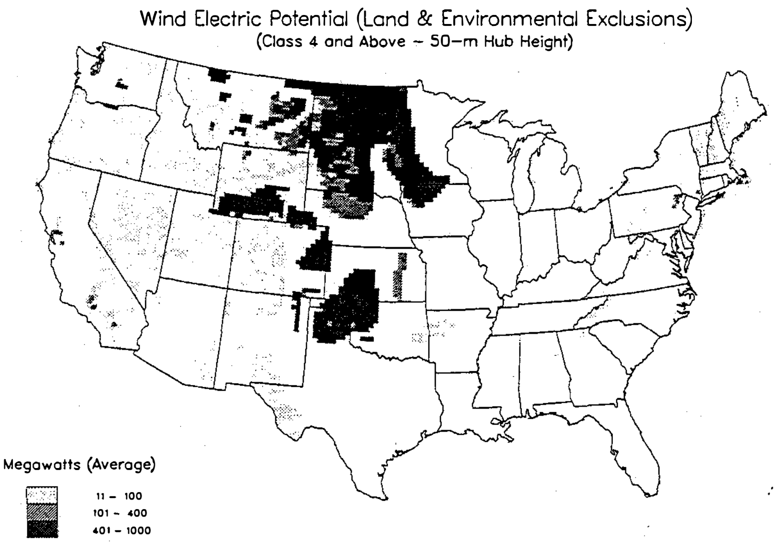

FIGURE 1. WIND ELECTRIC POTENTIAL FOR THE CONTIGUOUS UNITED STATES (CLASS 4 AND ABOVE, 50-M HUB HEIGHT)

CONVERSION OF WIND ENERGY INTO ELECTRICITY

Wind energy is captured by turbine blades that turn through interaction with air in motion, with mechanical shaft coupling to a generator that produces electricity. Figure 2 is a simplified schematic drawing of the major components of wind turbines, which include the rotor blades, gearbox, generator, nacelle, and tower.

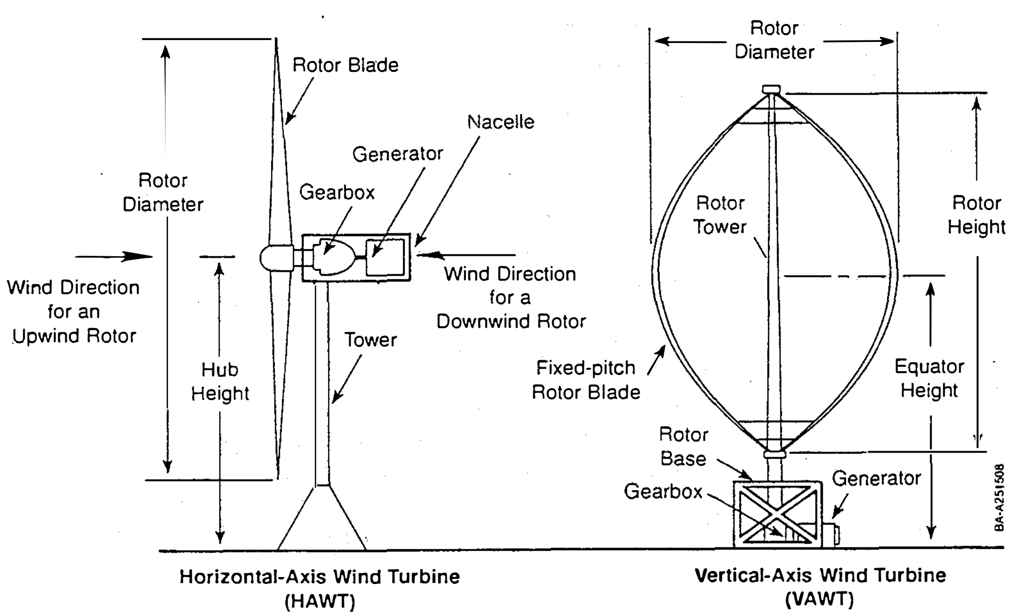

FIGURE 2. BASIC WIND TURBINE CONFIGURATIONS AND COMPONENTS

Modern turbines are either horizonal-axis or vertical-axis machines (see Figure 2) that make full use of lift-generating airfoils. Each type of turbine has advantages and disadvantages. Although both types are commercially available the horizontal-axis turbine is predominant. Horizontal-axis turbines are typically built with two or three blades. Turbines for utility applications are normally installed in clusters of 5 to 50 MW, which are called wind plants or wind farms. Modern wind turbines have efficiencies of about 40%, with availabilities typically exceeding 97%. Capacity factor (ratio of annual produced energy to annual nameplate energy) has typical values of 20% to 30%, which is very site specific as it reflects the fraction of the time that the wind blows. In areas of relatively constant winds (for example, trade winds), capacity factor can be as great as 60% to 70%. A description of various types of wind turbines is found in Eldridge [4].

HISTORY AND STATUS OF WIND ENERGY

More than 6 million windmills and wind turbines have been installed in the United States in the last 150 years, with the most common application being windmills used to pump water. Wind turbines, usually rated at 1 kW or less, were originally used to supply electricity to remote sites. The first large wind turbine was the Smith-Putman turbine, which was erected during World War II. It was rated at 1.25 MW of alternating current (ac) electricity and used a two-bladed metal rotor 53.3 m (175 ft) in diameter. By 1960 the production of wind turbine electric generators in the United States had essentially stopped, as most of the rural United States had been electrified via a grid of wires carrying electricity from more cost-effective, central fossil-fuel-fired generating stations.

The fuel oil uncertainties, fuel price escalations, and heightened environmental awareness of the 1970s brought a flurry of activity to develop cost-effective wind turbines. The U.S. Department of Energy (DOE) and the National Aeronautics and Space Administration led the activity by working with industry to develop wind turbines in various sizes for utility and remote applications. Most of the utility-size turbines (100–300 kW) were installed in California under lucrative power purchase agreements and favorable investment tax credits. The three primary locations are Altamont Pass and Tehachapi near San Francisco and San Gorgonio near Palm Springs. Figure 3 shows a typical wind plant. All of these turbines are significantly advanced beyond the technology of the older machines, although there are still opportunities for significant

FIGURE 3. A TYPICAL WIND FARM, SAN GORGONIO, CALIFORNIA

About 17,000 turbines with about 1600 MW of total capacity were installed in California, and significant installations are under way or planned in other parts of the United States. The turbines in the wind plants are usually privately owned, with the electricity sold to the local utilities. Europe is aggressively installing wind power plants and their installed capacity now exceeds that of the United States. About 4 billion kilowatt-hours (kWh) are produced annually in the United States from wind power plants [2]. The cost of electricity from current state-of-the-art wind plants is between $0.04 and $0.05 per kWh at the utility scale. This reflects significant advances over the last decade as indicated in Figure 4. For reference, about 40,000 MW of wind-generation capacity is required to displace 1 quad of primary energy consumption for fossil-fueled power generation.

POTENTIAL MARKETS

There are four major potential markets for wind power: 1) domestic utility grids, 2) foreign utility grids, 3) village power systems in developing countries, and 4) domestic remote-power systems. These markets vary in size and have different characteristics. The domestic and foreign utility grid-connected applications typically require larger (300 to 500+ kW) turbines installed in clusters of 5 to 50+ MW. These are large potential markets, with the foreign markets possibly developing earlier than the domestic market because the electricity often has greater value in the foreign markets. In addition, many of the potential foreign markets are in areas where a significant air quality improvement is required, which does not favor expansion of coal-fired generation plants. The village power market is significant because a large number of people (more than 2 billion) live without electricity, often in areas where a

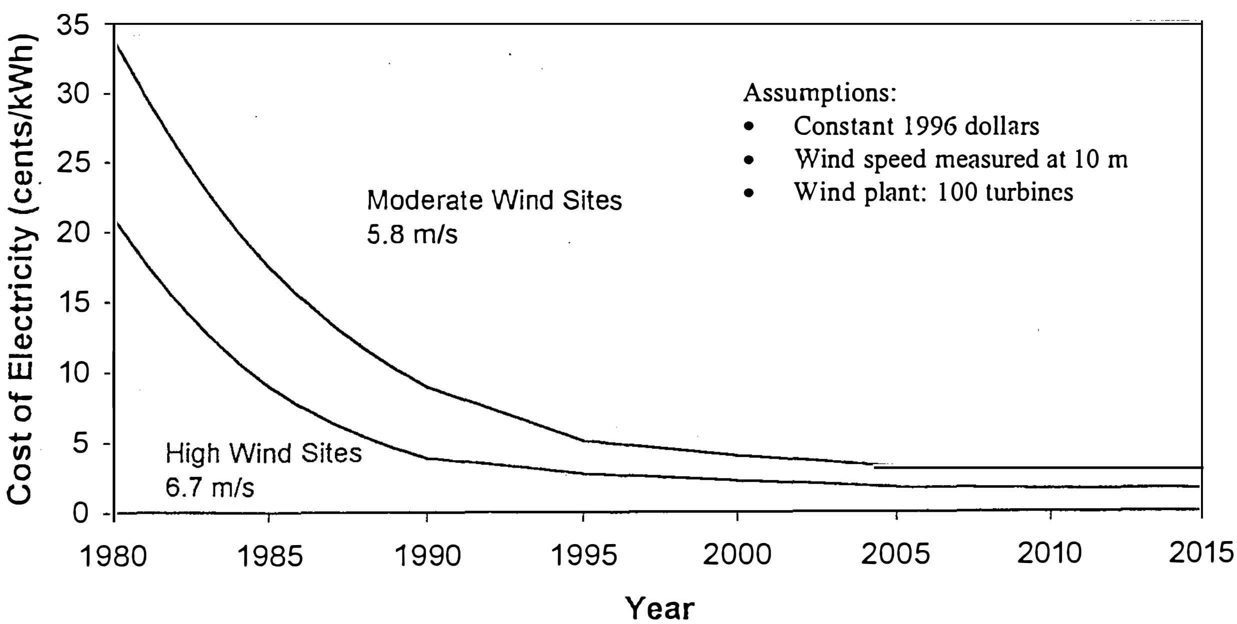

FIGURE 4. COST REDUCTION TREND

large grid construction or expansion is prohibitively expensive. Furthermore, the village power market is available now, with an important driving force being the need to stem the flow of individuals from rural areas to already overburdened cities of the Third World. In many cases, supplying electricity to rural villages will allow development of a local industrial economy, which results in jobs and a lessening of the incentive to migrate to a larger city. Often the power plant of choice for village power applications is a hybrid system, with wind turbines coupled to a diesel engine and often including other renewable energy sources and battery storage. The value of electricity for village power is much greater than that for large-grid utilities. The domestic remote-power market is relatively small and specialized. An example is powering remote telecommunication stations. This paper emphasizes the domestic utility market.

There is significant competition for supplying turbines and turn-key power systems to the above-mentioned markets. U.S. wind energy companies have significant competition, especially from European companies (primarily Danish and German). In many cases, a significant factor in choosing a supplier will be the availability of a financing package, especially for Third World applications.

COMPETITIVENESS AND SOME WIND ENERGY PROJECTIONS

The Energy Information Administration (EIA) provides an *Annual Energy Outlook* [2] with 20-year projections. Figure 5 is their projection for the energy use for electric generation for various modes of generation. The primary energy use for all electric generation is projected to grow from 32.59 quads in 1995 to 39.04 quads in 2015. The displacement of primary energy by use of renewable energy for electricity generation is projected to grow from 3.94 quads in 1995 to 4.90 quads in 2015. Figure 6 shows the projected growth in wind electricity generation from 3.93 billion kW in 1995 to 33.37 billion kW in 2015, with an average annual growth rate of 11.4%. Figures 7 and 8 indicate sensitivity of the projection to the rate of economic growth and to the price of petroleum. Note that the case of extreme growth is projected to be to as much as 58.35 billion kWh, or the displacement of as much as 0.6 quad of primary fossil-fuel energy through the use of wind energy.

These projections are somewhat lower than past DOE projections, which reflect factors that make it more difficult for wind energy to compete in the bulk-electricity market. The four primary factors are: 1) the availability of cheap fossil fuel, especially natural gas, 2) the impending

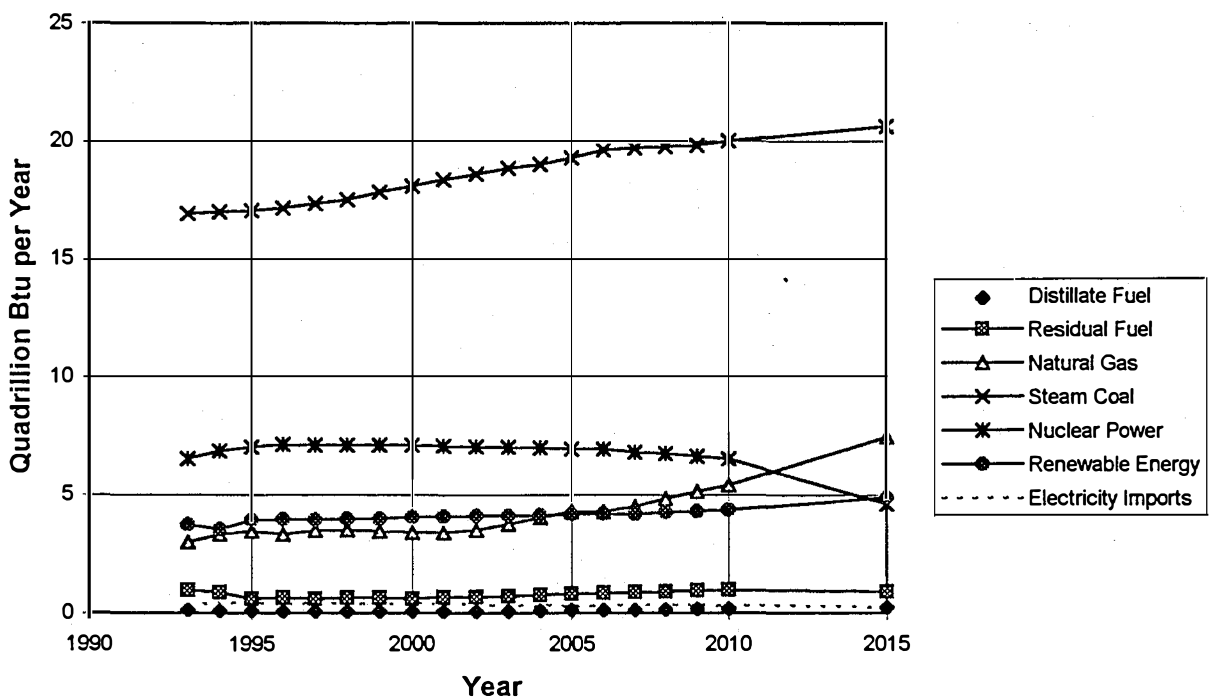

FIGURE 5. FORECAST UNITED STATES ELECTRIC GENERATION ENERGY USE

deregulation of the electric-utility market, which drives production toward the least available cost (currently, gas-produced electricity), 3) as wind-generation technology has improved, so have the competing generation technologies, and 4) external costs are not being fully reflected in the costs of generation, which favors use of fossil-fuel-based generation.

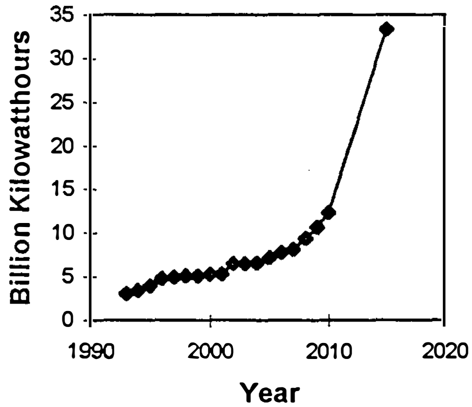

FIGURE 6. UNITED STATES ELECTRIC UTILITIES FORECAST WIND GENERATION

TECHNOLOGY DIRECTIONS

A goal of the research described in this paper is to position the U.S. Wind Industry to make much greater gains than projected by EIA. The general objectives of wind energy engineering are to reduce the cost of the equipment, improve energy capture from the wind, reduce maintenance, increase system and component lifetimes, and increase reliability, while at the same time being concerned with aesthetics and environmental effects. Studies are under way to define a development path to achieve full cost-competitiveness, with a potential and realistically achievable goal of about $0.025 per kWh at Class 5 wind sites. Cost reductions of this magnitude require numerous performance improvements, innovative components, manufacturing improvements and configuration changes, as no one technical change will give the required cost improvement.

DOE and its national laboratories, together with universities and the wind industry, are working together to accomplish these improvements through various research and development (R&D) programs. Each program has specific goals ranging from improving the current

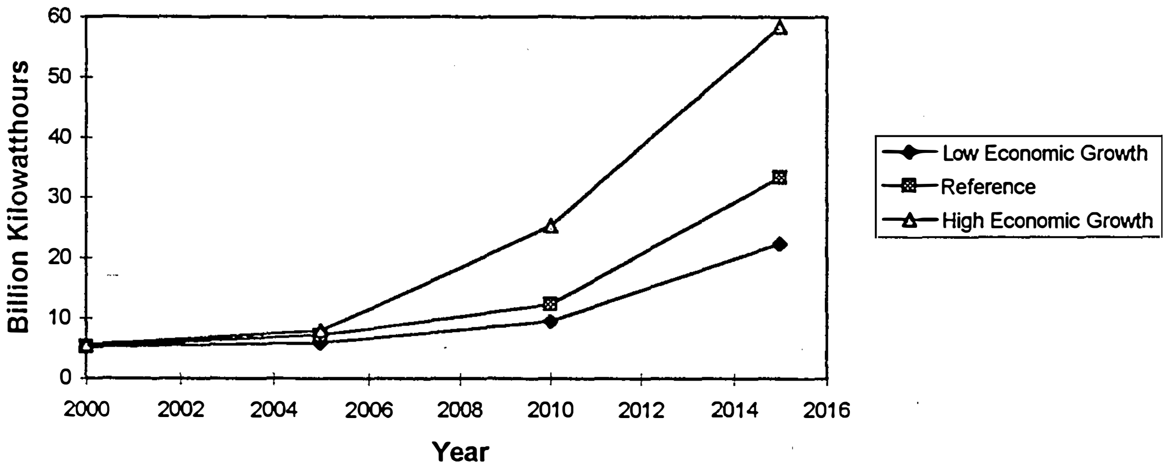

FIGURE 7. FORECAST WIND GENERATION; SENSITIVITY TO ECONOMIC GROWTH

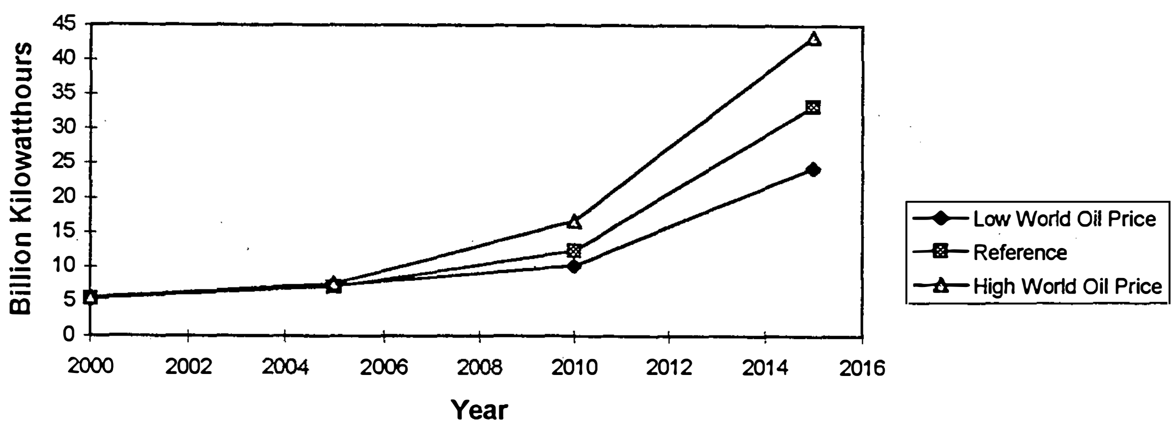

FIGURE 8. FORECAST WIND GENERATION; SENSITIVITY TO WORLD OIL PRICE

generation of turbines and components to defining, researching, and testing the innovative turbines of the next century. These programs also seek to develop a technology base that will enable the private sector to make the R&D advances needed to build a viable industry. Much of this R&D is cost-shared, with the industry and utilities typically supplying 30% to 70% of the funding.

Some of the potential changes that must be implemented in order to ensure a viable, cost-competitive industry include the following:

1) Better Turbine Configurations. Most turbines have been operated at constant speed, with typical rotor speeds of 40 to 60 revolutions per minute. This constant-input shaft speed is increased by using a gearbox, which gives a significantly higher generator speed. This results in a specified power quality of, say, 60 Hz. The power quality is closely controlled to ensure that wind plant electricity meets utility specifications. A more efficient approach is to allow the rotor to run at varying speeds as determined by the wind. Although this will result in potential energy production gains of about 15%, it will also require the use of sophisticated power electronics to change the output electricity from time-varying characteristics to the required time-invariant characteristics. An even more efficient approach is to eliminate the gearbox and to operate with a low-speed, direct-drive generator operated at variable speed. These approaches require that new power electronic control techniques and control equipment be developed, and that new types of generators be designed and developed.

The trend is toward larger turbines for utility applications. Most turbines are currently in the 300 to 500 kW range, with larger sizes being designed. This tends to reduce costs. The use of taller towers tends to enhance energy capture, because the theoretical relationship between wind speed and tower height is proportional to tower height raised to the one-seventh power.

2) Better Understanding of the Wind Resource and Tuning the Turbine to the Resource. This involves taking better measurements of wind characteristics, especially within wind plants, and developing better siting methods. Significant additional wind resource measurements are needed, especially long-term measurements to enable a better understanding of annual variation in the wind energy resource [1]. It is important that there be a better understanding of wind turbulence, and especially how local terrain and other structures generate turbulence. Turbulence within wind farms is greater than that in open terrain, as the former results in structural and fatigue loads that limit turbine component lifetimes or dictate maintenance schedules for turbines and components such as gearboxes [5]. It appears that there is a coherent structure to some of the turbulent flows generated from upwind turbines and terrain. Research is under way to allow prediction and mitigation of turbulence-induced loads [6]. Wind forecasting is another important factor in allowing wind plant operators to better plan and control operations. In addition, proper siting (for example, micrositing) can serve to maximize wind plant output, thus substantially enhancing income from the plant. This will only occur, however, when wind characteristics are better understood. Energy capture from the wind can also be maximized by tuning the turbines. Tuning variables include rotor diameter and airfoil shape.

3) Better Design Tools. Substantial effort is being devoted to developing computer characterizations of every component in the integrated wind turbine [7]. Objectives include understanding basic phenomena, load generation, and the load path from the tip of the blades to the turbine foundation. Methods of modelling all turbine components will also have to be examined. As a result, improved designs of components and systems will give rise to longer lifetimes and cost reductions. An additional goal is "virtual prototyping," in which validated computer models are used to understand the performance, lifetime, and cost of each component in a proposed design. Iterations to improve the designs will be done by computer, thus allowing the construction of significantly more advanced prototypes than those that would result if conventional design techniques were used.

4) Innovative Designs and Components Through Better Understanding of Phenomena. The National Renewable Energy Laboratory (NREL) has developed airfoils tailored to meet the specific demands of wind turbines [8]. This has resulted in greater efficiency of energy capture than was possible with the existing airfoils. These older designs, which were based on designs for helicopters, resulted in decreased efficiency when the airfoil's leading edge became fouled, as well as generator burnout due to excessive energy capture from wind gusts. The NREL airfoils are the first of a new generation of airfoils that will significantly improve performance and make wind energy more competitive in areas with wind power densities lower than Class 4. Energy capture gains of up to 30% have been accomplished for stall-regulated turbines using the NREL airfoils.

Time-variant, three-dimensional aerodynamic phenomena are significantly more complex than those observed in steady, two-dimensional wind tunnel tests. In collaboration with university and industry researchers both here and abroad, NREL researchers are generating better field data to provide an enhanced understanding of the basic aerodynamic phenomena [9]. The approach is to perform both wind tunnel and field tests with very sophisticated and rapid data collection systems that will aid in the understanding of boundary layer flow over the blade. In addition, dynamic stall is thought to be an important factor in determining mechanical loads on a turbine, especially when the blades experience transients (periods in which the blades go in and out of stall regimes). Objectives include understanding the basic phenomena, and defining and implementing simple mechanical modifications to minimize the resulting structural loads. The result will be better design methods and improved turbines.

Work is under way to better predict the effects of fatigue—the most important factor in determining turbine and component lifetime—on component design [10]. Further materials and structures testing, in addition to the computer modelling described above, may result in more robust and innovative designs. However, because turbine components are subject to fluctuating, random loads, they are much more difficult to characterize and design than would be the case with static loads.

5) Better Control Systems and Power Electronics. This involves using power electronics to generate higher quality electricity at a higher efficiency, and using better control techniques to enhance turbine operational efficiencies. These advances are possible because of improvements in computer techniques, some of which include fuzzy logic, neural networks, and other adaptive control schemes. Increased use of these techniques should serve to increase efficiency, reduce structural loads, and ensure higher quality power.

6) Innovative Manufacturing Techniques.
composite materials, better designs, and more cost-effective manufacturing techniques are needed for components such as blades. Blades are usually fiberglass composites or wood laminates, although some of the earlier large machines used aluminum blades. The current technique for manufacturing fiberglass blades is hand lay-up, which is labor intensive and difficult to control for quality. Substantial gains can potentially be made by using other techniques that are more automated. With good maintenance, the life of a utility-quality turbine is about 30 years, whereas a blade has a life of about 15 years. This means that the blade will need to be replaced during the lifetime of the turbine. Therefore, one goal will be to achieve blade life equivalent to turbine-unit life.

7) Mass Production. This will substantially reduce the cost of turbines. General use of advanced manufacturing techniques and standardized modules will also reduce costs.

INTEGRATION ISSUES

Wind energy is not considered dispatchable because of the variable nature of the resource. The ability to accurately forecast both short- and long-term wind patterns, coupled with innovative siting techniques, should result in a more constant output of wind-generated electricity. The use of multiple wind plant sites within a region, especially where the correlation between windiness at sites is understood, can potentially result in a situation in which the output of one wind plant can increase when the output of another decreases because of wind fluctuations. Accurate forecasting can significantly enhance the value of wind-generated electricity; a recent investigation indicates that the value increase can be as much as $0.01 to $0.02 per kWh [11].

Energy storage presents a significant technical challenge that could enhance the dispatchability of wind plants. Batteries, pumped hydro, compressed air, flywheels, and superconducting magnets are candidate storage techniques. A recent investigation indicated that for utility applications, pumped hydro energy storage is most cost effective [12]. For smaller applications such as village power, battery storage can be cost effective, especially in hybrid systems in which a diesel engine is included and the cost of diesel fuel is very high. When storage is integrated with wind plants, the value of wind-generated electricity will be much greater than the current value, which, for utility applications in the United States, has historically been considered equal to the avoided fuel cost.

Transmission access is important, especially in sparsely populated states such as Montana where wind resources are very substantial. In such an area, it would be necessary to transmit electricity from large wind plants to distant population centers. If existing transmission lines were available and if they had adequate capacity, the economics would be substantially better than if new lines had to be constructed at a typical cost of about $1 million per mile. Wind plant access to transmission lines may actually be enhanced by building fossil-fueled plants nearby to enable maximum utilization of the investment in the transmission lines. Obviously, this is a very location-specific situation, but one which is important to the economics of building large wind plants.

ENVIRONMENTAL ISSUES

The environmental benefits of wind energy are significant. Each 1 billion kWh of electricity generated by wind saves the equivalent of 1.8 million barrels of oil, and avoids emission of about 950 million pounds of carbon oxides and about 4.8 million pounds of other air pollutants.

However, some environmental concerns—particularly the death of birds that fly into operating turbines— must be addressed. There are numerous investigations under way to determine the significance of the problem, and to define and validate mitigation techniques. A typical example is the investigation being performed by researchers from the University of California at Santa Cruz [13]. Researchers there are collecting data in an attempt to understand the effect of wind turbines on the population of golden eagles in one section of the Altamont Pass wind resource area. The approach is to radio-tag and track sufficient numbers of eagles so that the population dynamics can be understood. Other researchers are investigating mitigation techniques such as eliminating tower members suitable for bird perching, using acoustic warning devices, painting appropriate warning colors and patterns on turbine blades, controlling vegetation around the towers to minimize prey availability, and siting wind plants with greater care. This is an emotional issue, with arguments ranging from doomsday to the other extreme that the avian population is actually increasing because of the wind turbines. Although avian problems are not thought to be widespread, this is a significant issue that is being addressed in a very serious and scientific manner.

Another concern is aesthetics. What is beautiful to an engineer may simply be ugly to others. Therefore, wind plant siting and layout are important. It appears that wind plants that have an orderly layout in rows may be preferable to layouts that follow ridges and flow patterns. In general, smaller wind plants with more plants at multiple sites may be preferred to one very large plant. Meeting these aesthetic criteria is a challenge that can be met by developing and using better siting guidelines, and by better educating the public about the value of wind plants.

CONCLUSIONS

Wind energy will be one of the most important, and most frequently applied, of the renewable energy sources during the next several decades. There are substantial problems to be overcome, but all appear solvable. A strong U.S. wind industry will be competitive in supplying wind turbines to the rest of the world, with significant environmental and societal benefits.

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