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WIND ENERGY AS A SIGNIFICANT SOURCE OF ELECTRICITY

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Wind energy is a commercially available renewable energy source, with state-of-the-art wind plants producing electricity at about $0.05 per kWh. However, even at that production cost, wind-generated electricity is not yet fully cost-competitive with coal- or natural-gas-produced electricity for the bulk electricity market. The wind is a proven energy source; it is not resource-limited in the United States, and there are no insolvable technical constraints. This paper describes current and historical technology, characterizes existing trends, and describes the research and development required to reduce the cost of wind-generated electricity to full competitiveness with fossil-fuel-generated electricity for the bulk electricity market. Potential markets are described.

THE RESOURCE

Winds arise because of the uneven heating of the earth's surface by the sun. One way to characterize winds is to use seven classes according to power density: class 1 is the lowest and class 7 is the greatest. The wind power density is proportional to the wind velocity raised to the third power (velocity cubed). For utility applications, class 4 or higher energy classes are usually required. Class 4 winds have 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) measured at a height of 10 m. Researchers estimate that there is enough wind potential in the United States to displace at least 45 quads of primary energy annually 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 30 quads of primary energy to generate electricity in 1993 [2]. A quad is a quadrillion (10^{15}) BTUs or about equivalent to the energy in 167,000,000 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 Great Plains states. 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 the article by Schwartz [3].

CONVERSION TECHNIQUES

Wind energy appears to be a conceptually simple technology: a set of turbine blades driven by the wind turns a mechanical shaft coupling to a generator which produces electricity. Figure 2 is a simplified schematic drawing of wind turbines, showing the major components. These include the rotor blades, gearbox, generator, nacelle and tower. It is the reduction of this simple concept to practice which results in significant engineering and materials challenges. The general goals 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 addressing aesthetics and environmental effects. This requires significant efforts in fundamental aerodynamics, materials engineering, structures, fatigue, power electronics, controls, and manufacturing techniques.

Modern turbines are either horizonal-axis or vertical-axis machines, Figure 2, that make full use of lift-generating airfoils (older generation windmills relied primarily on drag forces rather than aerodynamic lift forces to turn the rotor). Each type of turbine has advantages and disadvantages. Both types are commercially available although the horizontal-axis turbine is predominant. Horizontal-axis turbines are built with differing numbers of blades, typically two or three. Turbines for utility applications are normally installed in clusters of 5 to 50 MW which are called windplants 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 field value

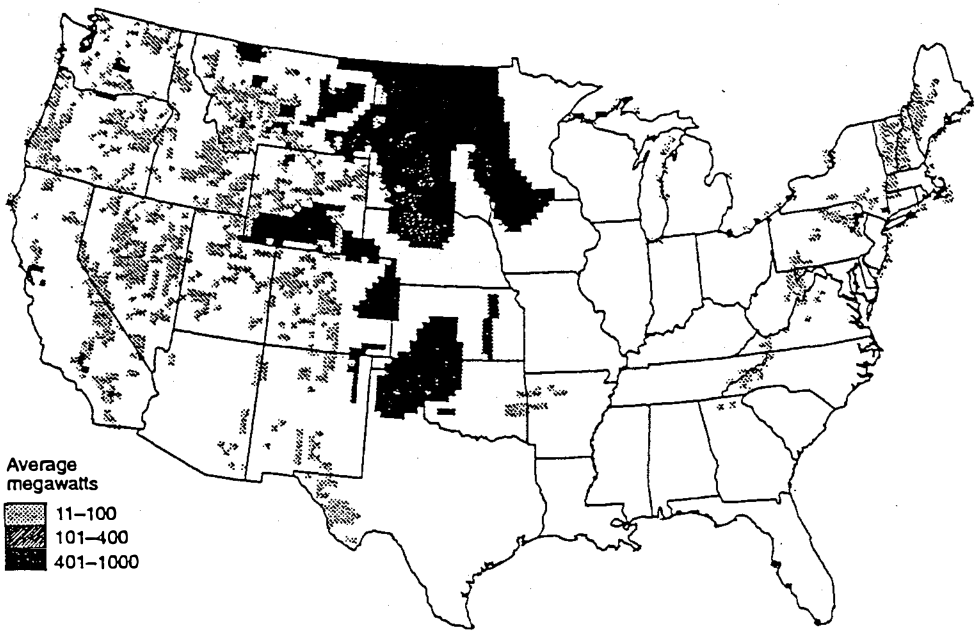

Figure 1. WIND ELECTRIC POTENTIAL FOR THE CONTIGUOUS UNITED STATES (CLASS 4 AND ABOVE, 50-M HUB HEIGHT)

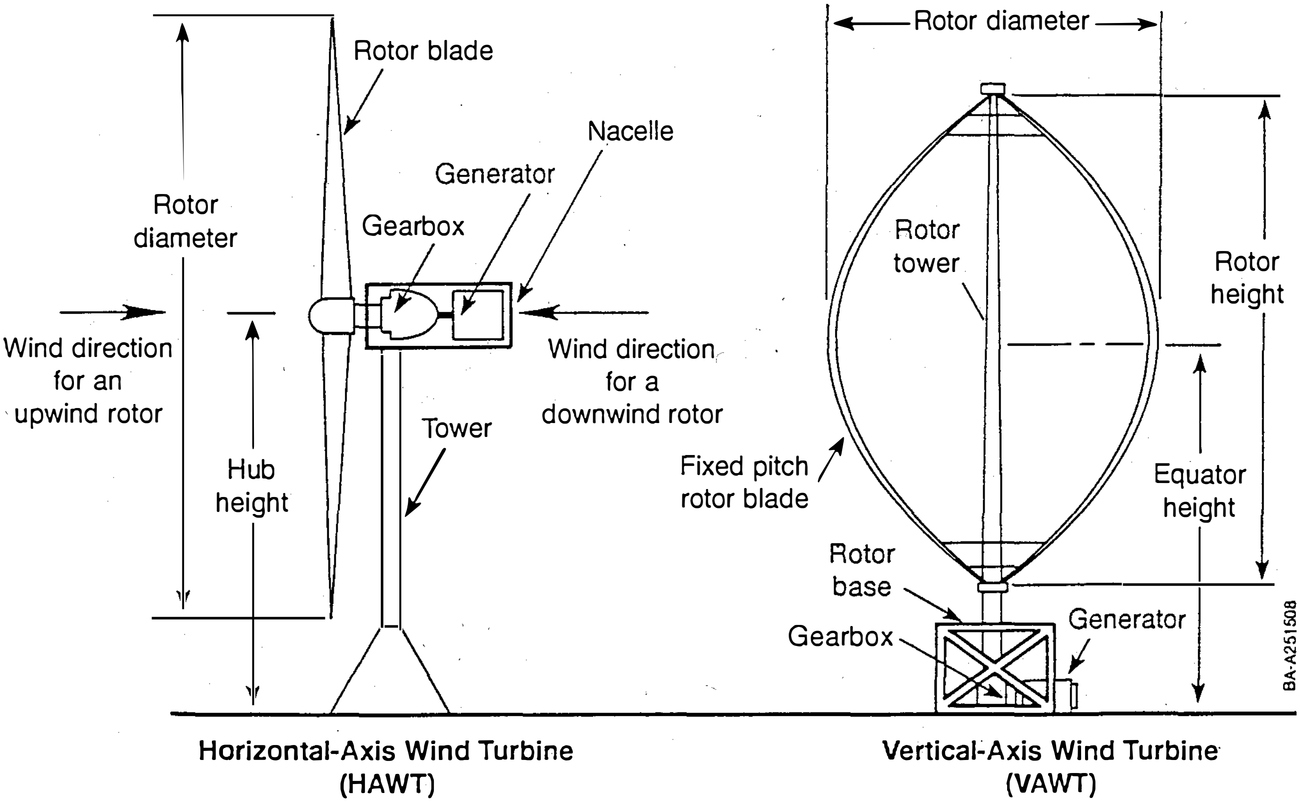

Figure 2. BASIC WIND TURBINE CONFIGURATIONS AND COMPONENTS

of 20 to 25%. Capacity factor is very site specific because it reflects the fraction of the time that the wind blows. In areas of relatively constant winds, e.g., 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

More than six million windmills and wind turbines have been installed in the United States in the last 150 years. Most were windmills with a rating of less than 1 hp. The most common windmill application has been water pumping, especially on remote farms and ranches. Wind turbines, usually rated at 1 kW or less, were originally used to supply electricity to remote sites. Typical is the Jacobs turbine, tens of thousands of which were produced from 1930 to 1960. The first large wind turbine was the Smith-Putman unit, which was erected in southern Vermont 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 turbines 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-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 (NASA) led the activity by developing large machines rated up to 4.5 MW. These large research and development machines had mechanical and structural problems, and efforts were stopped before the technology reached maturation. Nevertheless, these machines provided valuable experience and proved the value of many technical innovations. None of these large turbines are currently operating in a utility system. Numerous other machines (rated at 50–300 kW) were developed by industry in the 1980s and installed to produce electricity that was fed into the utility grid. Smaller turbines (1–10 kW) were developed for remote applications. All of these turbines were significantly advanced beyond the technology of the older machines, although there were still opportunities for significant improvements.

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 near San Francisco, Tehachapi near Bakersfield, and San Gorgonio near Palm Springs. Figure 3 shows a typical wind plant. The turbines were of widely differing quality, as were the developers and operators of the wind plants. However, after a sorting-out period, well-managed and well-operated wind plants resulted.

CURRENT STATUS

More than 16,000 wind turbines are currently installed in California with a total generating capacity approaching 1700 MW. The turbines in the wind plants are privately owned, with the electricity sold to the local utilities. These turbines generate more than 3 billion kWh of electricity per year—enough electricity to meet the residential requirements of a city of about 1 million people. This combined capacity is equivalent to a medium-sized nuclear plant. About 1% of the electricity used in California is generated from wind. Figure 4 shows a production history for U.S. wind turbines, most of which are located in California. For reference, about 40,000 MW of wind-generated electricity is required to displace 1 quad of primary energy consumption for fossil-fueled power generation.

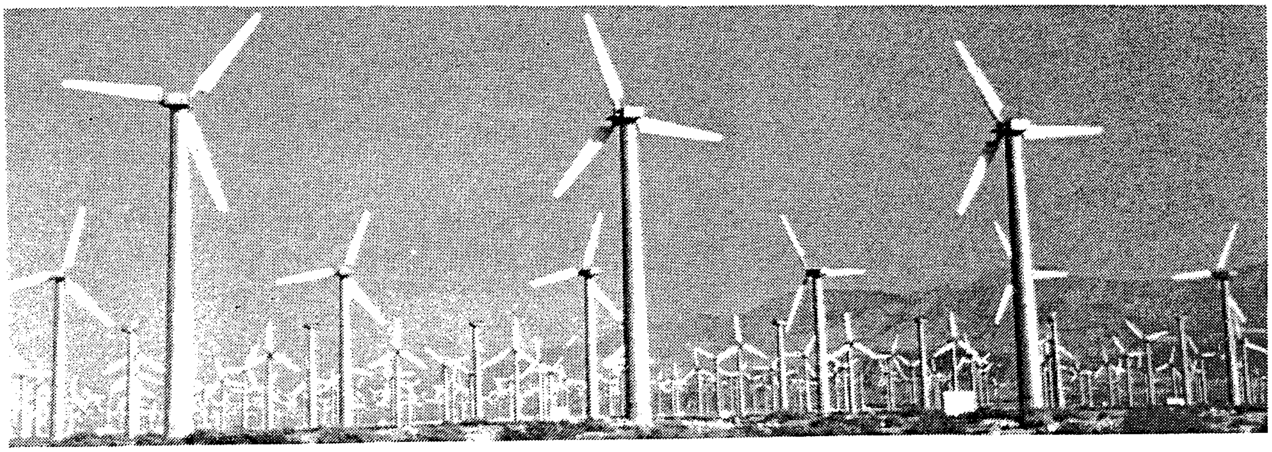

Figure 3. A TYPICAL WIND FARM - SAN GORGONIO, CALIFORNIA

DOE, through the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories, has research and development programs to improve or define the turbines of today, tomorrow, and the next century. The approach is to develop a technology base which will enable the private sector to perform the final development necessary to build a viable industry. Much of this research and development is cost-shared, with the industry and utilities typically supplying 30% to 70% of the funding. Current market projections from DOE estimate that 2% of the 2010 U.S. electricity supply will come from wind energy.

COSTS AND GOALS

Most of the early wind farms in California used early 1980s technology to produce electricity at a cost of $0.07–$0.10 per kWh, depending on the location, design, and operating policy. State-of-the-art plants are being built to produce electricity at a selling price of less than $0.05 per kWh at class 4 or greater wind sites. Around the year 2000, when the innovative next-generation wind turbines begin operating, the cost of wind-generated electricity is estimated to drop to less than $0.04 per kWh [5] at these sites.

Still, there are obstacles to widespread commercialization of wind energy. Wind energy technology has made substantial advances, but the competing technologies have also improved and the competitive situation has changed as the available supply of inexpensive natural gas has significantly increased. In addition, there is a potential change in the electric power industry to provide a structure which will result in increased competition. This change will probably enhance electricity generation by independent power producers, with an optimizing criterion being minimum cost of electricity. External costs, such as pollution avoidance and damage, are being discounted or totally ignored. This tends to make it more difficult for wind-generated electricity to effectively compete. Simply put, technical advances will have to cut the cost of wind energy even further for the DOE projections to become reality. The required technical advances appear achievable with sustained research and development.

POTENTIAL MARKETS

There are 4 major potential markets: 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 (300–500+ kW) turbines installed in clusters of 5–50+ 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 (> 1 billion) live without electricity, often in areas where a large grid construction or expansion is prohibitively costly. 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 in large grid utilities. Finally, the domestic remote power market is relatively small and specialized. An example is powering remote telecommunication stations.

There is significant competition for supplying turbines and turn-key power systems to these markets. The United States must compete with European companies, primarily Danish and German companies. In many cases, a significant factor in choice of supplier will be the availability of a financing package, especially for third world applications.

TECHNICAL CHALLENGES

Advanced wind turbines must be more efficient, more robust, and less costly than current turbines. DOE, its national laboratories, universities, and the wind industry are working together to accomplish these improvements through various research and development programs. Each program is aimed at specific goals ranging from improving the current generation of turbines and components to defining, researching, and testing the innovative turbines of the next century. The technical challenges these programs will have to address include the following:

Better characterization of 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. A better understanding of turbulence within the wind, and how local terrain and other structures generate turbulence, is needed. Turbulence within wind farms is greater than that in open terrain, resulting in structural and fatigue loads which limit turbine component lifetimes or dictate maintenance schedules for turbines and components like gearboxes [6]. It appears that there is a coherent structure to some of the turbulent flows generated from upwind turbines and terrain. Research is underway to allow prediction and mitigation of turbulence induced loads [7]. Wind forecasting is an important factor to allow the operators to better plan and control operations. Micrositing is important to maximizing wind plant output—proper siting can substantially enhance the income from a wind plant.

More efficient airfoils

NREL has developed airfoils tailored to meet the specific demands of wind turbines [8]. This has resulted in greater efficiency of energy capture (10-30%) than was possible with the existing airfoils. Older airfoils, which were based on designs for helicopters, have major problems: a decrease in efficiency when the airfoil's leading edge becomes fouled, and generator burn-out because of 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.

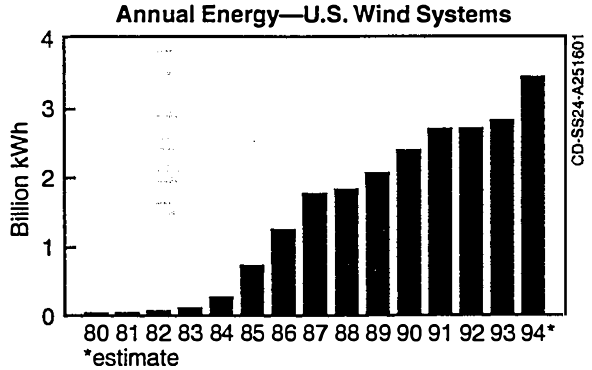

Figure 4 . COMMERCIAL WIND ENERGY IS A SIGNIFICANT PART OF THE U.S. ELECTRICAL SUPPY

Better blade manufacturing

Better 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. This technique is labor intensive and quality is difficult to control. Substantial gains can potentially be made by using automated techniques. The life of a utility-quality turbine with good maintenance is about 30 years, with the blades having a projected life of about 15 years, which necessitates a replacement of blades during the turbine life. A goal is to achieve blade life equivalent to turbine unit life.

Better understanding of aerodynamics

Time-variant, three-dimensional aerodynamic phenomena are significantly more complex than those observed in steady, two-dimensional wind-tunnel tests. NREL researchers are generating better field data to provide an enhanced understanding of the basic phenomena [9]. There are significant interactions with universities, industry, and foreign researchers in the area of fundamental aerodynamics. The approach is to perform both wind tunnel and field tests with very sophisticated and rapid data collection systems to understand boundary layer flow over the blade. Dynamic stall is thought to be an important factor determining mechanical loads on a turbine, especially when the blades experience transients in which they 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.

Development of theoretical models and computer codes

Substantial effort is being devoted to developing computer characterizations of every component in the integrated wind turbine [10]. Objectives include understanding basic phenomena, load generation and the load path from the tip of the blades to the turbine foundation, and how to model dynamic loads for the integrated wind turbine. As a result, improved designs of components and systems will give rise to longer lifetimes and will allow cost reductions while meeting the structural requirements of the components. A 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 on the computer, allowing the first physical prototypes which are constructed to be significantly advanced beyond those which would result if conventional design techniques were used.

Better understanding of fatigue and structures

Work is under way to better predict fatigue effects on components [11]. The goal is more robust and innovative designs. Research includes significant materials and structures testing, in addition to the computer modeling described above. Fatigue is the most important factor in turbine and component lifetime. Turbine components are subject to fluctuating random loads, which are much more difficult to characterize and design for than static loads. Testing is an integral part of blade development.

Better turbine configurations

Most utility-scale turbines have been operated at constant speed, with typical rotor speeds from 40 to 60 rpm. This constant input shaft speed is increased through use of a gearbox to give a significantly higher generator speed which results in specified power quality, say 60 Hz. The power quality is closely controlled to ensure wind plant electricity meets utility specifications. A more efficient approach is to allow the rotor to run at varying speed as determined by the wind. This will result in potential energy production gains of about 15%, but necessitates 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 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.

Better control techniques

This involves using power electronics to generate higher quality electricity at a higher efficiency and the use of better control techniques to enhance turbine operational efficiencies. These advances are possible because of the improvements in computers. Some of the techniques being considered include fuzzy logic, neural networks, and other adaptive control schemes. Not only should efficiency be enhanced, but it should be possible to reduce structural loads while ensuring higher quality power.

INTEGRATION ISSUES

Wind energy is not considered a firm power source by utilities because of the variable nature of the resource. 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/kWh [12].

Energy storage is an important technical challenge that could enhance the dispatchability of wind plants. Batteries, pumped hydro, compressed air, and superconducting magnets are candidate storage techniques. A recent investigation indicated that for utility applications, pumped hydro energy storage is most cost-effective [13]. For smaller applications such as village power, battery storage can be cost-effective. This is especially the case 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 probably be much greater than the current value, which for most utility applications in the United States is presently considered equal to the avoided fuel cost.

Transmission access is important, especially in sparsely populated states with very substantial wind resources, such as Montana. If a number of large wind plants were constructed in a sparsely populated area, it would be necessary to transmit the electricity to the distant population centers. If existing transmission lines are available and if they have adequate capacity, the economics will be substantially better than if new lines must 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

Wind energy is environmentally positive. Annual wind generated electricity production in California displaces the energy equivalent of 5 million barrels of oil and avoids the release of 2.6 billion pounds of greenhouse gases per year, in addition to avoiding other emissions such as sulfur and nitrogen oxides which contribute to smog and acid rain.

However, some environmental concerns must be addressed. The death of birds by flying into operating turbines is a concern, especially when the birds are raptors such as golden eagles. There are numerous investigations under way to determine the significance of the concern, 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 [14]. Researchers are collecting data to understand the effect of wind turbines on the population of golden eagles in one area of the Altamont Pass wind resource area. The approach is to radio-tag and track a sufficient number 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, appropriately painting warning colors and patterns on turbine blades, controlling vegetation around the towers to minimize prey availability, and siting turbines more carefully. The avian situation is an emotional issue, with arguments ranging from doomsday to the other extreme that the population is actually increasing because of the wind turbines. While avian problems are not thought to be widespread, this is a significant issue which 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 which follow ridges and flow patterns. In general, use of small wind turbine clusters located at multiple sites may be preferred to one very large plant. Aesthetics 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.

CONCLUSION

Wind energy will be one of the most important, widely applied of the renewable energy forms during the next several decades. There are substantial challenges to be met, but all appear solvable. Successful research and development will potentially result in generation from wind energy of about 10% of the electricity used in the United States. A strong U.S. wind industry will be competitive to supply wind turbines to the rest of the world, along with the significant environmental and societal benefits of wind energy.

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