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Low Wind Speed Technology Development in the U.S. Department of Energy Wind Energy Research Program

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LOW WIND SPEED TECHNOLOGY DEVELOPMENT
IN THE U.S. DEPARTMENT OF ENERGY WIND ENERGY RESEARCH PROGRAM

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ABSTRACT

The United States Department of Energy (DOE) Wind Energy Research Program has begun a new effort to develop wind technology that will allow wind systems to compete in regions of low wind speed. The sites targeted by this effort have annual average wind speeds of 5.8 m/s measured at 10-meter height. Such sites are abundant in the United States and would increase the land area available for economic development twentyfold. DOE has initiated a three-element approach through a competitive request for proposals. The three elements in the RFP include concept design, component development, and system development. This work will build on previous activities under the WindPACT Program and the Next Generation Turbine Program. The new program is targeting a levelized cost of energy of 3 ¢/kWh at low wind speed sites by 2010 and supports the U.S. wind industry's goal of reaching an installed domestic wind capacity of 100 GW by 2020.

NATIONAL ENERGY POLICY PRIORITIES

The United States is facing many challenges as it prepares to meet its energy needs during the twenty-first century. Electricity supply crises in California, fluctuating natural gas and gasoline prices, heightened concerns about the security of the domestic energy infrastructure and of foreign sources of supply, and uncertainties about the benefits of restructuring are all elements of the energy policy challenge.

In May 2001, the President's National Energy Policy Development Group released a set of recommendations that have become the cornerstone of U.S energy policy under the George W. Bush Administration (1). Pursuant to the release of the National Energy Policy recommendations, Secretary of Energy, Spencer Abraham, described the three priorities of the Department of Energy as:

- Ensuring energy security by strengthening the energy production and delivery infrastructure
- Focusing on programs that increase the supply of domestically produced energy, that revolutionize how the country approaches conservation and energy efficiency
- Directing research and development (R&D) budgets at ideas and innovations that are relatively immature and ensuring the greater application of mature technologies.

The Assistant Secretary of Energy Efficiency and Renewable Energy, David Garman, stated that implementation of the Secretary's priorities will involve nine elements (2). These include:

- Reducing dependence on foreign oil
- Reducing the burden of energy prices on the disadvantaged
- Increasing the efficiency of buildings and appliances
- Reducing the energy intensity of industry
- Creating a domestic biomass industry.

Most relevant to the Wind Energy Research Program is the priority to:

> "Increase the viability and deployment of renewable energy, by developing a diverse portfolio of renewable energy technologies that reduce the average cost of renewable energy production by 20% by 2010 and achieving cost-competitive parity with the average cost of energy by 2020."

CURRENT MARKET SITUATION AND POTENTIAL OPPORTUNITIES

Competitive cost of energy (COE) levels have been achieved by focusing development on class 6 wind resource sites (average wind speeds of 6.4 m/s @10 m height) and by taking advantage of the production tax credit (1.7 ¢/kWh in 2002 $). With favorable financial terms, class 6 sites can market electricity at prices of 4 ¢/kWh or less before the subsidy. However, as more sites are developed, easily accessible prime class 6 sites are disappearing. In addition, many class 6 sites are located in remote areas that do not have easy access to transmission lines. The full development of accessible class 6 sites may cause wind energy growth to plateau in the near future unless improvements in technology can make lower wind speed sites more cost effective.

Class 4 wind sites (5.8 m/s @10 m) cover vast areas of the Great Plains from central and northern Texas to the Canadian border. Most of North and South Dakota are swept by class 4 winds. Class 4 sites are also found along many coastal areas and along the shores of the Great Lakes. While the average distance of class 6 sites from major load centers is 500 miles, class 4 sites are significantly closer, with an average distance of 100 miles from load centers. Thus, utility access to the class 4 sites is more attractive and less costly. Much more importantly, these class 4 sites represent almost 20 times the developable wind resource of class 6 sites. Figure 1 shows regions with class 4 and greater resources.

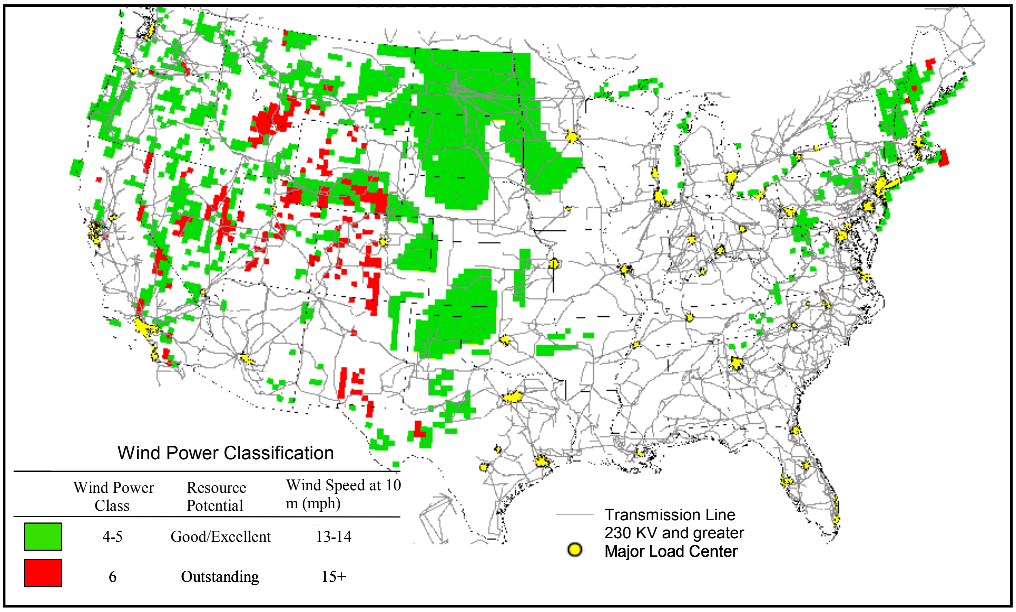

FIGURE 1. MAP SHOWING THE WIDESPREAD AVAILABILITY OF CLASS 4 AND CLASS 5 RESOURCES COMPARED TO THE MORE LOCALIZED AVAILABILITY OF CLASS 6 RESOURCES.

Currently wind energy at class 4 sites can be marketed at prices in the range of 5 to 6 ¢/kWh. Advanced low wind speed technology will be required for wind technology to be cost-competitive at class 4 sites.

Low Wind Speed Technology Goal

The program has defined goals for its technology development activities that will position wind as an attractive advanced technology option for the twenty-first century. The low wind speed technology (LWST) goal is:

- Reduce cost of energy from large wind systems to 3 ¢/kWh in class 6 wind resources by 2004, and to 3 ¢/kWh in class 4 wind resources by 2010. (compared to a 2002 baseline of 4 ¢/kWh in class 6 and 5.5 ¢/kWh in class 4)

Capacity Addition Benefits of Low Wind Speed Technology

DOE researchers have developed an estimate of the additional capacity that could be installed in the United States as a result of the development of LWST. Their projections were developed using the National Energy Modeling System (NEMS), DOE's primary electricity sector modeling tool. If a turbine capable of producing electricity for 3 ¢/kWh in class 4 sites became available in 2007, the NEMS projected wind capacity in 2020 would be about 60 GW or 45 GW above what might otherwise be expected. If the turbine became available in 2010, the 2020 estimate would decline somewhat to about 50 GW or 35 GW more than the baseline expectation. Both cases represent a significant benefit to the nation. Both of these projections assume that there is no long-term production tax credit–a key objective of the low wind speed technology program is to eliminate the need for on-going subsidies.

The additional 45 GW of capacity would require over $30 billion in private sector capital investment, which would provide significant economic benefits to rural landowners and enhance energy security and environmental protection efforts. The low wind speed technology project is, therefore, closely aligned with the National Energy Policy goals described earlier in this paper.

In addition to activities to develop large-scale wind systems, DOE's Wind Energy Program also supports the development of distributed (<100 kW) wind system technologies to help distributed wind systems achieve the same cost-effectiveness in class 3 (5.3 m/s @10m) by 2007 as they currently have in class 5 (6.2 m/s @10m) resources. This will open up new energy options for consumers in a wide range of applications–homes, farms, remote villages, water pumping, and battery charging.

Wind Program Structure

In response to the new National Energy Policy priorities, DOE's Wind Energy Program recently began charting new directions for its efforts. These directions are being organized around the two thrusts described by Assistant Secretary Garman. They are:

1. Increasing the viability of wind energy–developing new cost-effective technology for deployment in less-energetic, class 4 wind regimes (see figure 2); developing cost-effective distributed, small-scale wind technology; and laying the groundwork for future work to tailor wind turbine technology to the production of hydrogen
2. Increasing the deployment of wind energy–helping facilitate the installation of wind systems by providing supporting research in power systems integration, resource information, market acceptance, and industry support.

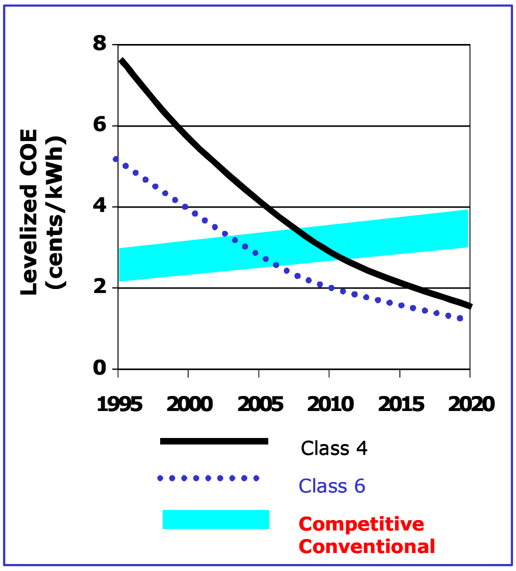

FIGURE 2. LEVELIZED COST OF WIND ENERGY FROM CLASS 4 AND CLASS 6 TURBINES COMPARED TO A BAND OF COSTS FOR CONVENTIONAL GENERATION

LOW WIND SPEED TECHNOLOGY DEVELOPMENT ACTIVITIES

The development of low wind speed technology is a priority strategy being pursued to increase the viability of wind energy. At the heart of this new research plan, is the development of wind turbine technology (machines larger than 100 kWs) that is capable of producing electricity for 3 ¢/kWh at class 4 sites by 2010. This objective will be achieved by bringing to bear all the resources of the Department of Energy, its laboratories, and a wide array of industry partners. The development of low wind speed technology, planned as a cooperative effort with industry, will be guided by several principles:

- Program experience and stakeholder input will provide strategic input.
- Program evaluations performed regularly using performance-based management techniques will provide a strong analytical basis for performance criteria, periodic review, and adjustment.
- Public/private partnerships will be developed to support continuing innovation. They will be flexible and adaptive, support multiple pathways, and offer repeated opportunities for new players to enter the program.

The LWST project is structured around three elements, as shown in Figure 3. In addition, it is supported by on-going program activities in wind systems integration and supporting research and testing. The program currently envisions that the LWST project will represent an increasingly large portion of total program funds over the remainder of this decade.

Since the late 1980s, the program has emphasized a public/private sector partnership in which new turbine designs are cost-shared and led by industry, while the Federal laboratories, the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL), provide the theoretical support through applied research and feedback from performance testing. Industry partners make commercial decisions, and the laboratories, via the National Wind Technology Center (NWTC), transfer improved technology to industry while providing unique testing services not otherwise available to them. The level of cost-sharing required depends on the size of the procurement and the accompanying technical risk, and is consistent with guidance provided in the Energy Policy Act of 1992.

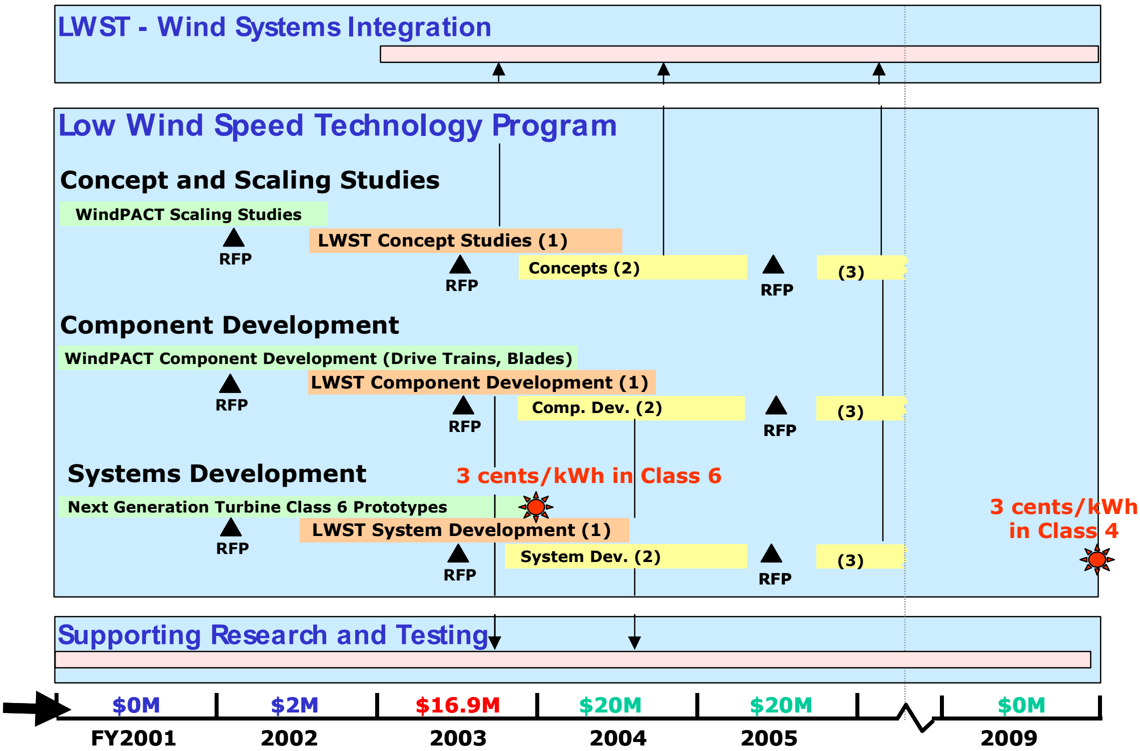

FIGURE 3. TIMELINE FOR THE LOW WIND SPEED TECHNOLOGY PROJECT, SHOWING THE THREE PROGRAM ELEMENTS AND THE THREE PHASES OF EACH ELEMENT.

The low wind speed technology project began with a request for proposal (RFP) issued October 19, 2001. The RFP offered bidders an opportunity to participate in one of three technical areas; 1) concept and scaling studies, 2) component development, and 3) low wind speed turbine prototype development. This RFP offers industry partners several different approaches to the problem of synthesizing new systems designs. Because different project teams may be at different stages of systems development, additional RFPs will be issued within the next one to two years. These new opportunities to participate will allow partners to take the results from one technical area and move into another. An example would be completing a systems design study under the first RFP and proposing on a component development effort in a later RFP. These later RFPs also represent additional points of entry into the program for industry partners who are not currently ready to submit a proposal. Proposals have been evaluated and negotiations have begun with six prospective awardees in the three technical areas.

LOW WIND SPEED TECHNOLOGY DESIGNS–EVOLUTION VS. REVOLUTION

The low wind speed technology project is tightly focused on hardware improvements. A myriad of design approaches for decreasing COE has been proposed and many explored at some level. COE reductions over the past two decades have resulted from the combination of many improvements in a wide range of areas, including manufacturing, engineering, and business practices. Although turbine size has increased significantly, wind turbines today look much like they did 10 years ago. Design changes are visible only to the most knowledgeable observer. Will the wind turbine of tomorrow look much different? DOE laboratories and industry have been conducting studies to try and answer this question and better understand the course of future technology (3, 4, 5).

Some of the more important findings of these studies include:

- No single technology improvement or innovation will achieve the LWST goals.
- Taller towers are important for improved energy capture at low wind speed sites.

- Advanced blade designs and materials are necessary.
- All rotor configurations can be optimized equally to help improve COE.
- Transportation and crane erection limitations must be overcome.
- Advanced controls are extremely important for loads alleviation.

COE reductions will be the result of combining a number of technical improvements. Some potential examples are:

- Advanced rotors and controls -15% ± 7%
  (Flexible, low-solidity, higher speed, hybrid carbon-glass, and innovative designs)
- Advanced drive train concepts -10% ± 7%
  (Hybrid drive trains with low-speed permanent magnet generators and other innovative designs, including reduced cost power electronics)
- New tower concepts -2% ± 5%
  (Taller, modular, field assembled, and load feedback control)
- Improved availability and reduced losses -5% ± 3%
  (Better controls, siting, and improved availability)
- Manufacturing improvements -7% ± 3%
  (New manufacturing methods, volume production, and learning effects)
- Region and site tailored designs -5% ± 2%
  (Tailoring the designs of turbines for unique sites of larger [100 MW] wind farms)

MEETING THE TECHNOLOGICAL CHALLENGES

While the findings from the DOE/industry studies seem straight forward, each represents a significant technological challenge.

Aerodynamic Predictions (Unsteady Stall)

Studies at the NASA Ames wind tunnel in 2000 demonstrated serious deficiencies in all available codes for predicting aerodynamic loads. Primary weaknesses exist in predicting how rotors handle the unsteady stall effects they encounter during a wide range of operating conditions. Accurate loads prediction is a key element in reliable wind turbine design. The aerodynamic loads drive the design of almost all wind turbine components. While the inaccuracies of existing design codes have been dealt with by increased design safety factors, future COE reductions will depend heavily on reducing such factors based on more accurate predictions and measurements. A key objective of the Wind Energy Research Program is the design of newer, more accurate codes based on sound physics principles that account for better characterization of turbulent inflow conditions. These new design codes will use the large suite of data accumulated in the controlled conditions of the NASA Ames wind tunnel to ensure their accuracy.

Great Plains Winds

The Great Plains region of the United States represents immense wind energy potential. Class 4 sites abound. Initial studies have shown that wind shears of greater than 1–7 are common. Shears of .2 and .3 have been recorded, indicating that significant additional energy exists at higher altitudes above ground. Maximum energy can be captured by using larger rotors on much taller towers as shown in Figure 4. Tower heights of 100 to 150 meters are projected. But accompanying these greater wind shears are other poorly understood effects associated with a phenomenon known as the nocturnal jet. During day/night transition periods, as solar heating decreases, the planetary boundary layer (PBL) stratifies, bringing the high velocity winds aloft closer to the Earth's surface. This change causes unpredictable mixing between the two layers creating high velocity shifts that can cause large-scale coherent turbulent structures to tumble along the PBL. This turbulent mixing region often dips as low as 80 to 100 meters. Design codes and safety factors currently being used may not adequately handle these poorly understood conditions. Studies using the most advanced tools to quantify and characterize these effects are underway. Tall tower studies will gather more detailed information about wind shears and three dimensional wind structures. These studies will also explore the use of ground based profiling equipment based on laser Doppler measurement (LIDAR) and acoustic sounders (SODAR) that may allow site assessments without the erection of very tall towers. These studies will eventually link inflow conditions at higher hub heights to actual machine performance and provide designers information and computer codes necessary to design structures capable of handling these turbulent conditions.

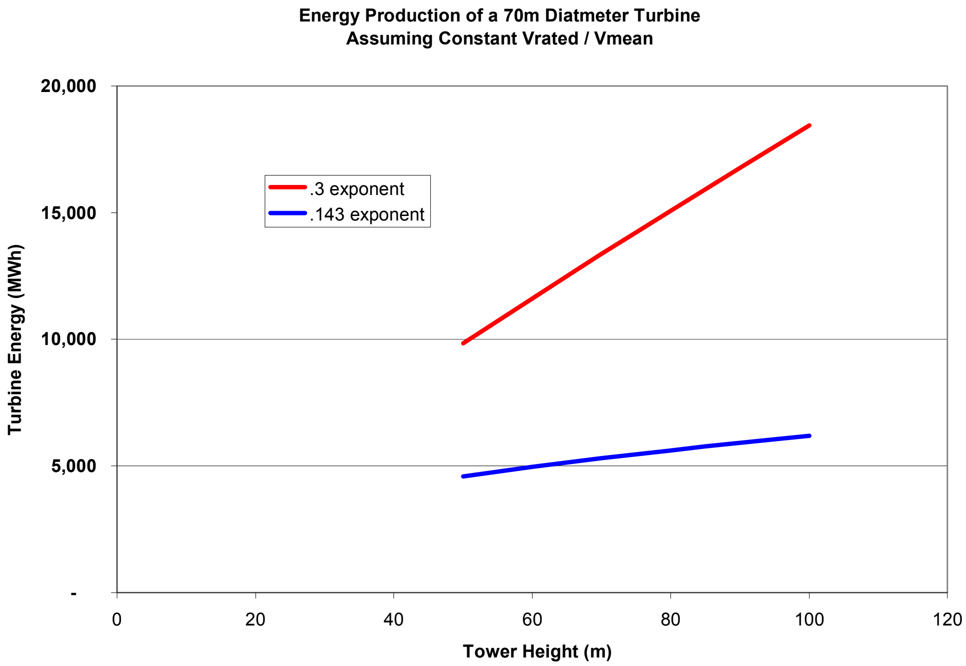

FIGURE 4. INCREASE IN AVAILABLE ENERGY DUE TO HIGHER WIND SHEARS.

Advanced Materials and Designs

Wind turbine rotor and blade designs are among the most important elements of wind turbine designs. As rotors grow in size, rotor mass would normally be expected to increase as the cube of the rotor diameter. Blade costs normally increase directly as the mass of the blade increases. Studies show that blade designers have avoided this cubic increase by employing innovative internal design techniques. But the ability of basic fiberglass design and fabrication techniques to avoid this cubic increase appears to have run its course. As machines increase in size, above 1.5 MW, greater design innovation will be required. The introduction of new materials with improved design characteristics is imperative. Carbon fibers and fabric, as well as innovative design techniques are being explored by laboratory and industry designers to determine optimum techniques for incorporating these new materials into new designs (3).

Higher Efficiency Drive Train Components

The components necessary for conversion of rotor torque to electrical power represent almost 50% of the initial capital cost of the wind turbine. A 1% change in drive train conversion efficiency causes a nearly equivalent change in the cost of energy. New design studies conducted by DOE subcontractors are exploring a range of drive train innovations, like those illustrated in Figure 5, that would have the net effect of both increasing efficiency and decreasing capital cost. Most of these innovative designs rely heavily on new low-cost permanent magnet generators as well as new design configurations.

Other aspects of electrical conversion that appear to present opportunities for improvement are power converters (power electronics) that provide the dual advantage of allowing variable speed operation while controlling torque and power quality.

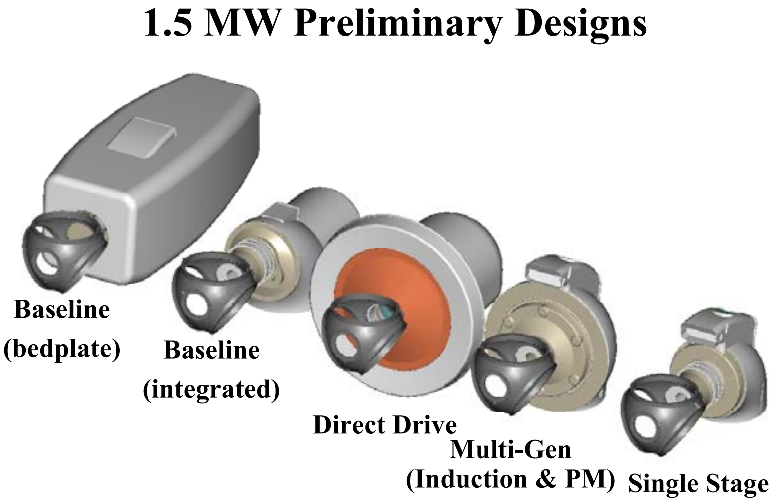

FIGURE 5. INNOVATIVE DRIVE TRAIN ALTERNATIVES.

Scaling and Logistics

Wind turbines have generally grown in size in the last decade. The average machine of 2002 is roughly 1 MW, compared to the average machine of 1992 at 100 kWs. The last 10 years have shown that larger machines can generally be manufactured and installed more economically and produce energy at decreased costs. Many commercial machines being sold in the United States in 2002 are in the 1.5 to 1.8 MW range. Larger machines are being developed in Europe, primarily for the off-shore market. However, as machines have grown, increases in capital costs, in addition to components costs, have begun to be realized. Larger machines require larger components such as blades and towers. Transportation and erection of these components are potentially a limiting factor on the deployment of machines of greater than 2 MWs in the Great Plains. Shipping envelope limitations can have significant cost impacts. Components of greater than 4.9 meters in diameter incur significant cost premiums for transport. In some cases, these limitations can restrict erection to certain times of the year. In other cases, they severally limit transportation routes. Taller towers and heavier components also impact the cost of erection. Above certain height and weight envelopes, cranes capable of performing the necessary lifts are rare and costs for deployment of such machines can start to approach the cost of the turbine itself. Significant innovation in on-site fabrication and assembly are important to continued growth. Studies by DOE and industry (4, 5) are exploring concepts that are expected to contribute to cost-effective development of larger machines on taller towers on the Great Plains. These concepts include; hybrid towers, use of advanced composites, unique structural elements, and the inclusion of self-erecting capabilities into tower structures (See Figure 6). In addition to these tower approaches, unique blade fabrication facilities, capable of being deployed at or near a new wind turbine development, can reduce the impact of blade transportation costs.

THE WIND TURBINE OF THE FUTURE

Will the machine producing electricity for 3 ¢/kWh in 2010 in a Great Plains site look drastically different than a machine in a California pass in 2000? Unlikely. But beneath the shell improved technologies will be evident from blade tip to tower base and beyond.

The machine of the future is likely to consist of an innovative blade made from composites of advanced carbon fabrics integrated into more conventional fiber-glass. The blade may use adaptive designs in which the blade loads cause the blade to twist in such a way as to reduce the loads. Blades will be longer and perhaps thinner, operating at higher tip speeds and taking advantage of an improved understanding of aerodynamic loads and aero-acoustics. Rotors will mitigate loads through innovative independent blade pitch control algorithms based on feedback from blades, drive train, and towers. Drive trains will consist of single stage drives linked to lightweight, high power density permanent magnet generators. Or perhaps the drive train will have no gearing at all. Machines will be variable speed, processing their varying frequency power through an expanding range of power converters using new circuit designs and cheaper electronic components. Towers will soar to 150 meters and will erect themselves quickly. They will also be able to lower a machine to the ground in a matter of hours to allow major maintenance on the ground without the deployment of large cranes. And throughout, components and structures will be designed with an increased knowledge of turbulence and inflow in new environments and the use of more accurate codes that allow designers to reduce design factors based on improved certainty.

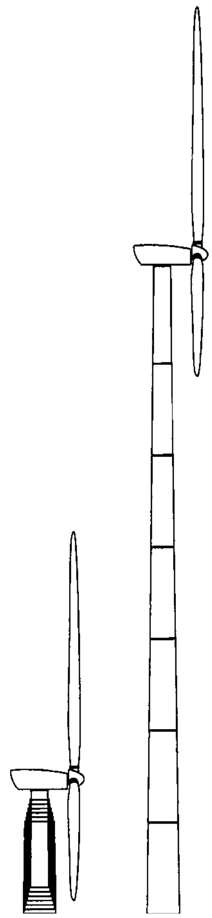

FIGURE 6. WINDPACT TELESCOPING TOWER CONCEPT

Wind turbines will still look like wind turbines. But the power produced by these mammoth machines of the future will compete head to head on a cost of energy basis with coal and natural gas.

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