Journal of Solar Energy Engineering

Discussions

U.S. Department of Energy Wind Energy Research Program for Low Wind Speed Technology of the Future

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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, and that revolutionize how the country approaches conservation and energy efficiency
- Directing research and development (R&D) budgets on 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], including:

- 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. Class 4 winds sweep across the majority of North and South Dakota. 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 Class 4 sites is more attractive and less costly. More importantly, Class 4 sites represent almost 20 times more developable wind resource than Class 6 sites. Figure 1 shows regions with Class 4 and greater resources.

Currently wind energy at Class 4 sites can be marketed at prices in the range of 5–6 ¢/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 to 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 U.S. 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. Assuming a turbine capable of producing electricity for 3 ¢/kWh in Class 4 sites became available in 2010, the NEMS projected wind capacity in 2020 would be about 50 GW or 40 GW above the baseline expectation, which represents a significant benefit to the nation. This projection as-

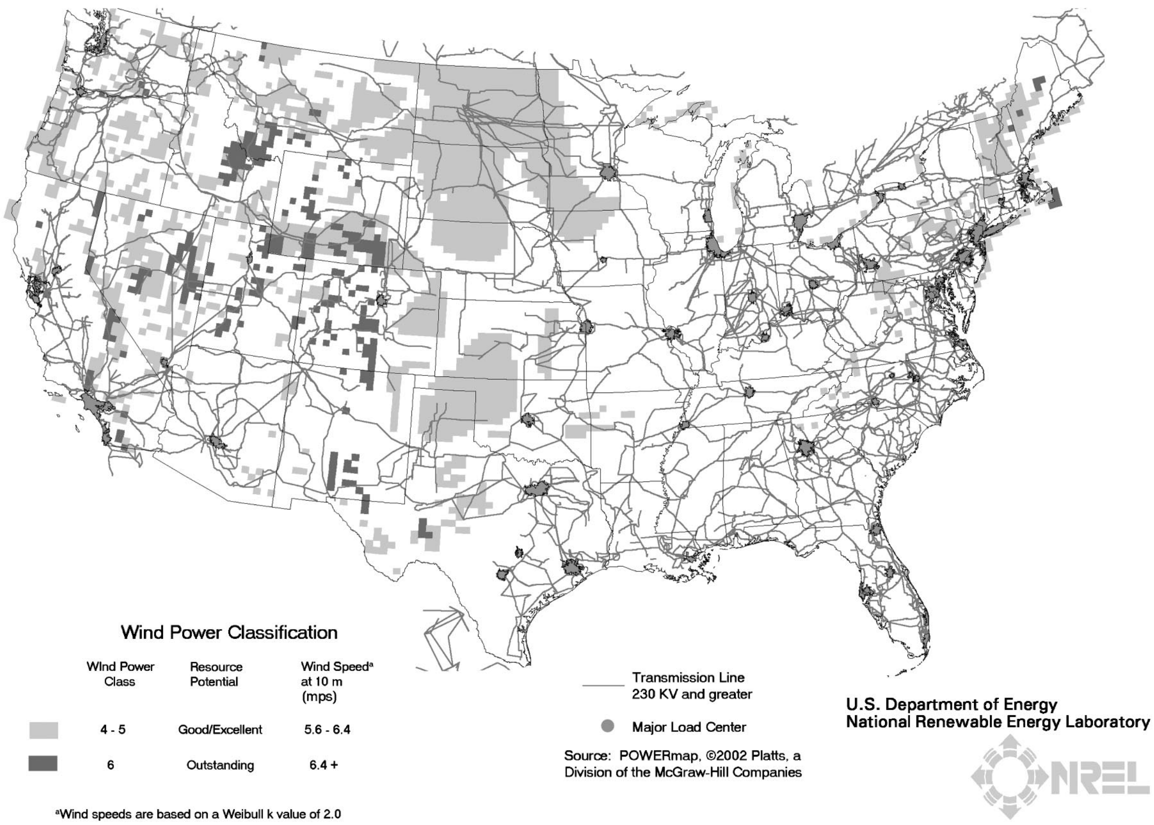

Fig. 1 Regions of U.S. with class 4 and greater resources

sumes 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 40 GW of capacity would require approximately $30 billion in private sector capital investment. This 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

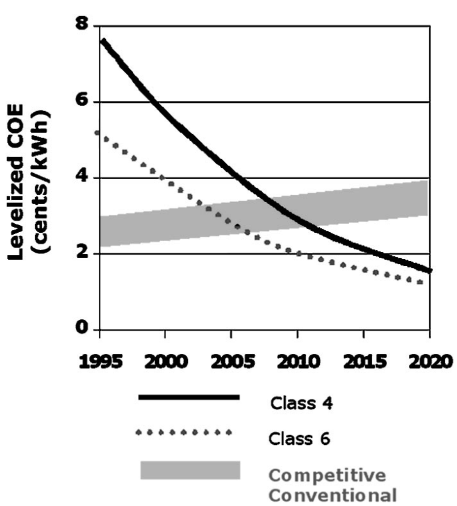

Fig. 2 Class 4 wind regimes

distributed (<100 kW) wind system technologies to achieve the same cost-effectiveness in Class 3 (5.3 m/s @10m) wind sites 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 National Energy Policy priorities, DOE's Wind Energy Program recently began charting new directions for its efforts. These directions are being organized around two thrusts described by Assistant Secretary Garman:

1. Increasing the viability of wind energy by developing new cost-effective technology for deployment in less-energetic, Class 4 wind regimes (see Fig. 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 by providing supporting research in power systems integration, resource information, market acceptance, and industry support.

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 kW) 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 expertise 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: concept and scaling studies, component development efforts, and full turbine system developments. In addition, it is supported by ongoing 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.

The low wind speed technology project began with a request for proposals (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 offered 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 1–2 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 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. Under the initial RFP, proposals have been evaluated and negotiations have begun with six prospective awardees in the three technical areas.

Low Wind Speed Technology Designs - Evolution versus Revolution

The low wind speed technology project is tightly focused on hardware improvements. Myriad design approaches for decreasing COE have 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 [3–5].

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).

The Wind Turbine Of The Future

It is unlikely that the machine producing electricity for 3 ¢/kWh in 2010 in a Great Plains site will look drastically different from a machine in a California pass in 2000. 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 with more conventional fiber-glass. The blade may use adaptive designs that 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 may 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 m 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. Components and structures throughout 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.

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

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U.S. National Laboratory Research Supporting Low Wind Speed Technology

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Harvesting wind energy from sites with lower annual average wind speeds at costs comparable to what can now be achieved in higher wind sites is an international challenge. It requires pushing the technology to optimize the use of materials and machinery and tuning the structure to withstand the loads unique to the lower wind speed sites. The U.S. Department of Energy's laboratories—The National Renewable Energy Laboratory (NREL) and Sandia National Laboratories—are engaged in both basic science and applied research to overcome current technology limitations and enhance the individual components necessary to achieve cost-effective low wind speed turbines.

Technology improvements are necessary in three principal areas to minimize the cost of electricity production at lower wind speed sites.

1. Turbine rotor diameters need to be larger, harvesting the lower energy winds from a larger inflow area. This must be accomplished without increasing the cost of the rotor beyond what a smaller rotor might cost in an energetic site.
2. Towers must be taller to take advantage of the increasing wind speed at greater heights. Again, the approach taken for these towers needs to be less costly than traditional approaches if the benefit from increased energy capture is to exceed increased tower costs.
3. Generation equipment and power electronics must be more efficient to accommodate sustained light wind operation at lower power levels without increasing electrical system costs.

Achieving equivalent or lower COE production for low wind speed sites is difficult. Increased energy capture cannot come at the expense of increased machine cost and fundamental technology advances are required if the cost goals are to be achieved. For example, stretching the rotor to improve capture area, a length squared effect, will have its benefits swamped by increased material usage, a length cubed effect, unless some changes in design approach or materials are made. The following discussion explains the research issues created by the need to meet the above goals.

Atmospheric Characterization

As both the rotor diameter and turbine hub height grow to extract more energy from the available wind resource, a better understanding of the inflow is necessary. Until now, most commercial turbines have operated at hub heights below 50 m in the sub-viscous region of the Planetary Boundary Layer (PBL). Here, the near surface heating effects produce a well-mixed and relatively homogeneous inflow boundary layer. As the hub height increases, the characteristics of the PBL change significantly as both surface heating and friction effects are reduced. At 100+ m, larger, more coherent flow phenomena, such as Kelvin-Helmholtz waves and the nocturnal jet, are formed. In addition to the more homogeneous small-scale turbulence experienced at lower-hub heights, large-scale coherent flow structures with characteristic length scales on the order of the turbine diameter will also be encountered. Thus, the potential for single-event turbine/coherent inflow structure interactions must be considered in addition to the more typical stochastic inflow events currently modeled.

A new understanding of this flow environment is being gleaned from both field measurements and numerical simulation. From these results, new inflow models are being developed to assess the performance of turbine designs incorporating larger diameters and taller towers. In the near term, field data collected on tall towers is being used to identify coherent inflow structures that produce the largest single event load histories. These structures are simulated analytically and used as dynamic inflow inputs for current aerodynamic and structural response models.

In a parallel research effort, computational models based on Reynolds Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES) methods are being used to model the development of large coherent vortical flows under conditions of neutral inflow boundary layer stability. These results provide additional inflow simulation input and will help establish similarity between computationally derived and measured inflow data. In addition, these models should provide some insight as to the frequency and extent of the coherent vortex/turbine rotor interactions that can be expected. Finally, more detailed inflow models based on better physical models must be developed. In the longer term, computational fluid dynamic (CFD) models will provide detailed, high fidelity inflow data based upon the underlying flow physics and local topography.

Rotor Loads and Controls

The new Low Wind Speed Turbines (LWST) will have larger diameters, taller towers, and proportionally lower tower top mass if cost targets are to be achieved. Thus, these new designs will be much more dynamically active and will need to respond to a more complex inflow environment with load mitigation strategies not currently employed. Significant improvements in the ability of the machine to sense the loads and reduce them at the rotor, before they begin to feed through the system, are critical.

There are several efforts currently in progress aimed at achieving this end. Control systems, including sensors, actuators, and software to connect the two, are an important part of the research effort. In the past, control systems have been collective in nature (operating on all the blades in unison) and have sought primarily to affect smooth power generation and maintain the desired rotor speed. Such systems are already seeing limited use to mitigate tower loads by controlling the rotor thrust and eliminating some large-scale turbulence loads. Future control systems will be able to sense the loads (or winds) locally and respond with each blade individually. Pitch control is the current option of choice of many turbine manufacturers, but activation devices that use local flow

[1]This work was performed at the National Renewable Energy Laboratory in support of the U.S. Department of Energy under Contract No. DE-AC36-99GO10337.

[2]Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin company, for the U.S. Department of Energy. This work is supported by the U.S. Department of Energy under Contract DE-AC04-04AL85000 and DE-AC36-83CH10093.

control to influence and mitigate turbulence driven loads may also be built into the blade. For example, twist-coupled blades that naturally change their angle of attack and reduce the load peaks in response to gusts are being investigated as a passive way to accomplish at least a portion of the desired load reduction.

As the complexity of the controller increases, there is a further need to improve the reliability of sensors, actuators, software, and all the moveable parts of the rotor control system. Control optimization and advanced multi-input, multi-output designs will be required. Substantial research is being devoted both to control development and to the ability to model the complete aeroelastic system in order to facilitate the transfer of advanced controls concepts from the laboratory to the commercial world. All of these control efforts are working toward the goal of enabling designers to stretch the rotors while holding down the loads that would increase structure costs.

Aerodynamics

Active turbine control will only be achieved if the aerodynamic loads from inflow/rotor interactions are well understood and properly modeled. ''On average'' knowledge and prediction of rotor loads is insufficient for a rapid response LWST control system that must literally ''fly'' a dynamically active soft turbine system in a complex inflow. The NREL full-scale wind tunnel test at the NASA Ames 80×120-ft. wind tunnel indicated that current design and prediction tools based on blade element momentum (BEM) theory perform well in conditions for which they have been tuned. They do not perform in novel and unusual environments like those anticipated for the LWST.

Aeroelastic and CFD tools validated with field and wind tunnel data offer the best approach for understanding the underlying flow structure and rotor loads. However, typical CFD models contain millions of nodes and take days of computation time using typical PC and workstation resources available to the wind industry. This time constraint neither meets the near real-time loads prediction needed for active control nor is attractive as a design tool when numerous design iterations are required.

Current research efforts to improve aerodynamic codes are split between furthering our basic understanding of the rotating, 3-D, unsteady separated flows experienced by turbines operating in the field and incorporating this knowledge into advanced predictive models for loads. A concerted effort is underway to enhance existing predictive codes with empirically derived modules to maintain computational speed and increase accuracy until we are able to bring CFD tools into the realm of everyday design usage.

Materials and Manufacturing

Even if improved controls are able to lower the dynamic blade loading, increased material stiffness will be necessary to prevent blade tower strikes and lower overall rotor costs. There has been great interest in the use of carbon fiber materials in blades to achieve these results; however, significant uncertainties remain with respect to how best to incorporate higher cost fibers into the blade design. Because the traditionally expensive carbon fibers drop in cost as the tow size (numbers of fibers in each bundle) increases, it is important to determine if these cheaper but stiffer fibers have a role to play in wind turbine blades. Material usage will also remain inefficient if the uncertainties in strength remain high, thereby mandating larger design margins. Extensive testing programs are required to establish strength and fatigue properties of these new materials, given the unique stochastic loading environments in which they must reliably perform.

With the development of much larger rotors and the associated incorporation of new materials, the manufacturing of blades becomes significantly more complicated. The wind industry is moving from traditional hand-lay-up fabrication methods plagued with high labor and inconsistent quality to resin infusion methods (VARTM, RTM) and pre-preg fabrication techniques. As carbon and carbon-hybrid materials are incorporated and unique laminate structures are proposed (e.g., off-axis for twist-coupled blades), new questions arise as to the fabrication efficiency and acceptance of this new technology by industry.

Many combinations of fiberglass materials, including braided, woven, stitched, and pre-preg constructs, are likely candidates for use in composite blade structures. Different forms of the same materials can have significantly different fatigue, strength, and handling properties. Trade-offs between materials, structure, form, manufacturing process, and design requirements must be made to obtain large, stiff, relatively light, yet economic blade designs. Research with industry participation will be required to validate these technologies in order to reduce risk, lower costs, and increase commercial viability.

Towers and Logistics

The connection between tower size and logistics is undeniable. With traditional tapered tower design, the taller the tower, the larger the base diameter becomes and the more troublesome manufacturing and transporting the tower become. Attention has, therefore, begun to shift away from the traditional concept of a tapered steel tower that is transported to the site as whole sections and bolted together to form the final structure. Some attention has been given to alternate tower materials with reinforced concrete because of its low cost. Guy-cables are getting a new look as a means of spreading the load at the tower base. Multiple sections welded in place on the site may be required to eliminate the need to move the enormous diameters of multimegawatt machines. Various other on site manufacturing innovations are also being investigated. Manufacturing towers on site provides an opportunity to merge the manufacturing and erection functions into a single operation, eliminating the need for the massive cranes that would otherwise be required to lift the heavy sections to great heights.

Generators and Power Electronics

The use of variable speed (VS) technology has significantly improved both energy capture and power quality; however, there are still significant advances that can be achieved. Much of the increased energy capture from the improved aerodynamics of VS operation is dissipated in the associated power conversion losses. Power electronics are most efficient at their maximum power rating, dropping off rapidly at lower power levels. Wind turbines often operate below 50% of their maximum power rating where the power conversion efficiencies are far from ideal. This operating characteristic represents a significant opportunity for the development of unique conversion architectures that maximize energy capture over the operating wind spectrum.

Tower-top weight constraints represent another significant opportunity. Optimum combinations of generator, gearbox, and drive train designs are required to achieve maximum energy capture and performance. With larger turbines, direct drive, permanent magnet machines offer the promise of lower maintenance costs as a result of the elimination of the gearbox. In contrast, single-stage gearbox designs can significantly reduce the generator size and reduce the tower top weight. Multiple gearbox designs offer both component redundancy and component assembly/replacement, minimizing the time required to make repairs. No clear cost or performance advantage has been gleaned from any of the current design alternatives. Ultimately, it will be the vertical integration and the optimization of the entire turbine system that produces the lowest overall machine cost for LWST applications.

Summary

The cost of electricity produced by wind turbines is already competitive at locations with excellent wind resources. While it may be several years before the U.S. has exhausted these prime wind development sites, more marginal wind resources at locations where transmission access and load proximity increase electricity market value are even now under consideration. Research efforts at the DOE National Laboratories are focused on making the economics of wind-generated electricity at marginal sites comparable with the economics at the best wind sites available today. There is no silver bullet that will drop the cost of energy with a single change in approach or technology innovation. Efforts across the gamut of technical specialties are being integrated and optimized in order make wind power the least expensive and most accessible power generation on the grid.

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