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Characterization of Wind Technology Progress

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CHARACTERIZATION OF WIND TECHNOLOGY PROGRESS

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INTRODUCTION

The U.S. Department of Energy (DOE) Wind Energy Program, the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories periodically re-evaluate their characterization of the state of wind technology and revisit wind research and development cost and performance goals. These characterizations, goals and supporting analyses are part of a larger effort in the DOE Office of Energy Efficiency and Renewable Energy to establish a consistent data base of technology progress information for its major programs. The data developed are used to communicate the competitive status of wind to various stakeholders, and to support various analytical exercises such as market impact studies and analysis of alternative research paths.

1995 marked the conclusion of a number of DOE-supported advanced turbine design efforts. Results from the next major round of DOE-supported research contracts are expected near the latter part of the century. This timing presents an opportunity for incorporating recent progress and results from the federal program, and from industry progress, into technology goals and projections for the end of the century and beyond. This paper discusses future trends for domestic wind farm applications (bulk power), incorporating recent turbine research efforts under significantly different market assumptions than assumed in previous DOE estimates. Updated cost/performance projections are presented, along with underlying assumptions and discussions of potential alternative wind turbine design paths. Additionally, issues regarding the market valuation of wind technology in a restructured electricity market are discussed.

TECHNOLOGY CHARACTERIZATION BACKGROUND

The U.S. Department of Energy (DOE) Wind Energy Program's current work in expressing wind technology trends for the U.S. bulk power market, termed "Technology Characterizations," (TCs) is the third in a series of efforts dating from 1989, at which time input was prepared for the National Energy Strategy. That initial work included an industry survey and the use of Electric Power Research Institute (EPRI) and other outside data, as well as national laboratory input.[1,2] The second effort in 1993 had a more detailed analytical basis, with information taken from the DOE/NREL Advanced Wind Turbine Near Term Conceptual Design Studies and other development programs of the period.[3,4] Current work utilizes data from ongoing DOE/NREL Next Generation Turbine Research, and other industry turbine development and DOE research efforts. The latter DOE information includes results from the recently-completed Near-Term Product Improvement projects and Next Generation Phase I Concept Definition Studies. Currently three contracts are under negotiation for design and prototyping of next generation turbines. DOE plans to complete an updated (1996) version of its "Technology Characterization for Advanced Horizontal Axis Wind Turbines in Windfarms" in July, 1996.

DOE technology characterizations are used for responding to numerous requests for an overall description of technology cost and performance trends. The data is commonly used to answer questions from a variety of private and government sources, to provide input for market studies, for internal DOE quantification of potential benefits from program research efforts, and as one of the inputs to the Energy Information Agency's (EIA) annual market projections.

ANALYTICAL BASIS FOR CHARACTERIZATIONS

Approach to Trend Description

The Technology Characterization is presented as time trends of sets of cost and performance figures ("figures of merit") for wind farms that are considered to be broadly representative of each time period. Characterizations for current and near-term technology are based on a composite description of existing and proposed machines. The decision to represent a composite is based on the recognition that there is more than one design currently on the market and that there is more than one pathway to improved cost and performance characteristics. For later years, a representative technology path is built up from broader expectations of advances in certain subsystems or in certain technology areas (such as materials).[5,6] In formulating overall cost and performance figures of merit, estimations of expected cost and performance improvements for particular turbine subsystems were compared against known overall bounds (such as the Betz limit, raw material cost, etc.) as a reasonability check on projections, particularly in study end years.

Composite descriptions of windfarm cost and performance are not projections of the future for specific turbine designs. Rather, they are constructed to represent projected overall trends. For instance, actual capital and O&M costs, as seen in the market, may not follow a smooth downward curve as shown in the TC. As new turbines are introduced, costs may be higher until production increases and sufficient experience with O&M is developed in the field. Thus, although one might expect to see a downward trend over time, the path may be "saw-toothed" along the way as new technology is developed. This will be especially true with a technology in the earlier phases of commercial maturity (such as wind turbines) when large improvements are realized with each new generation of technology.

Figure 1 shows composite trends expected in wind turbine development. One of the concepts that the figure illustrates is that while there may be incremental advances in the technology, (technology "jumps" from one horizontal arrow to another), at the same time, there is an ongoing process of optimization. (This is shown as the bottom arrow "feeding" the incremental improvements above). It is recognized that designs are not driven solely by economic and technical factors. Manufacturer inertia and the nature of the market will also dictate the length of time that design features remain in the market. Additionally, designs will be driven in part by the need to conform to certain design standards in order to receive certifications that enable sales in some areas overseas.

Uncertainty In Assumptions

There is a higher level of certainty regarding near-term characterizations. However, some uncertainty

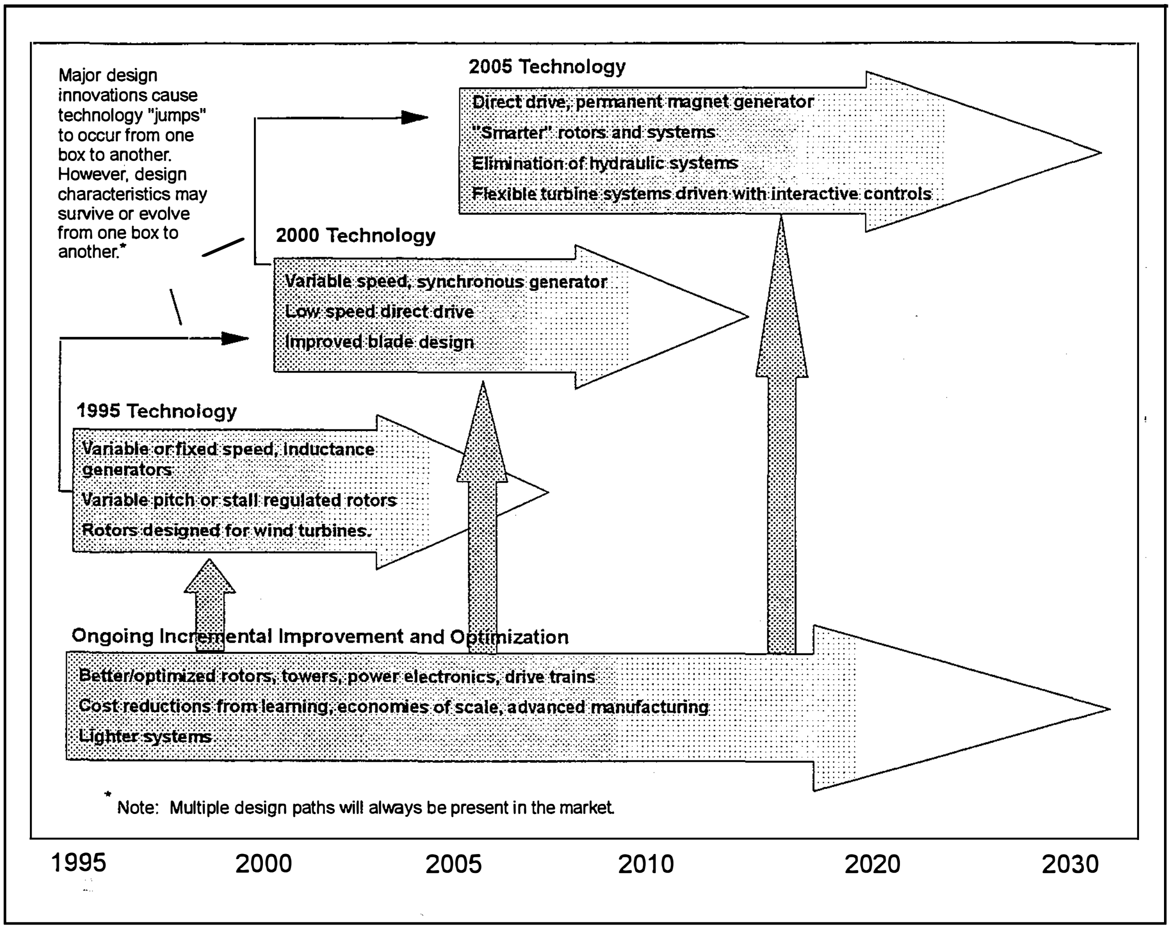

FIGURE 1. WIND ENERGY TECHNOLOGY EVOLUTION

exists even in these projections. The description of 1995 technology, for instance, is not considered validated until a sufficient number of turbines have proven their performance and operating cost characteristics over a number of years. A major source of uncertainty in turbine capital cost estimates comes from trying to infer turbine and windfarm costs from quoted prices. That is, pricing strategies can make it difficult to determine true costs. There are also key uncertainties in several assumptions made in the TC for combining cost and performance into an overall cost of energy (COE) figure of merit. These include values for balance of station (BOS) costs (all initial project costs other than the wind turbine capital cost), losses, and values of O&M. Although values for these assumptions have been formed from information collected from various industry and research sources, DOE welcomes additional industry and other stakeholder comment and input to improve the level of certainty regarding these values.

<u>Description of 1995 Technology</u>

1995 technology is a composite of fixed and variable speed options, but generally involves the use of one or more low cost induction generators. It is distinguished from earlier technology (1993 in the previous Technology Characterization) by the substantial use of power electronics (for power conversion and/or dynamic braking) and the use of NREL advanced airfoil designs. Projects using these types of technology currently exist. Turbine availability is high, and not expected to appreciably increase in following years. Windfarms for all years are assumed to be comprised of 100 turbines. A key assumption for 1995 technology is that costs are based on a cumulative production volume of approximately 500 units. This level of production serves as the baseline for future cost reductions due to volume effects.

2000 Technology Trends

Projections for the year 2000 include as their basis, information from the NREL Next Generation Turbine Research program. The direction of the 2000 technology, as reflected in the TC, is generally toward larger generators and rotors, variable speed or multiple speed, increased used of power electronics, more sophisticated control electronics, taller towers, and in some cases advanced generators. Figure 1 lists two alternative technology paths for 2000: 1) a variable speed synchronous generator with fully rated converter (electronics that allow elimination of the gear box), and 2) a doubly fed generator, that is seen as an interim, low cost variable speed generation option, with a geared transmission.

These two alternatives hardly begin to cover the possible configurations that could encompass, for example, vertical axis wind turbines, but they provide examples of potentially popular viable technologies for the time period. It is expected that all configurations for 2000 will incorporate advanced airfoils. It will be possible to design turbines for greater reliability based on a better knowledge of wind inflow characteristics and how they impact structural design, and appropriately improved modeling tools. It is expected that there will be improvements in turbine blades, particularly with respect to better integration of blade structural and aerodynamic design with appropriate manufacturing processes.

Progress is also expected in areas outside of cost and performance of the individual turbine. For example, more accurate micrositing models are expected to be developed, which will contribute to a reduction in wind farm array losses. Better local weather forecasting, along with appropriate utility operator training, is expected to raise the value of wind generation to the utility. A discussion of the importance of such value issues in today's market is found later in the paper.

2005 Technology Trends

Advances in 2005 are expected to be driven in part by an additional cycle of NREL-sponsored turbine development projects. As indicated in Figure 1, it is expected that a move will begin toward direct drive systems, with lower cost power electronics and increasing sophistication in control electronics, and rotor aileron or pitch activation. Permanent magnet generators may become cost-effective for wind farm-size turbines. The trend is expected to continue toward larger machines and higher towers in this time frame.

2010 and Future Technology

Performance gains are expected to level off in later years, with cost gains impacted primarily by volume effects (learning effects for customized components and volume discounts for off-the shelf components) and new manufacturing processes made viable by higher levels of turbine production. Specific technical advances are expected in the areas of materials (especially blade materials), advanced techniques and components to enhance turbine "load shedding" ability, and resultant ability to use larger rotor diameters (and so increase energy capture without increasing rotor efficiency). Continuing advances in electronics and electronics cost reduction are expected. Turbine generator rating is not expected to increase significantly during the period, as inverse economies of scale may hinder turbine development much beyond one megawatt.

QUANTIFICATION OF PERFORMANCE AND COST PROJECTIONS

For the trend information above to be fully useful in DOE program activities, expected progress must be quantified. Multiple metrics, or "figures of merit" are used in the characterizing progress. This is necessary in order to portray the three basic categories of performance advances, cost advances, and overall cost/performance ratio. Additionally, different figures of merit for each of these categories allows description of advances from a number of different perspectives. Presenting turbine efficiency, for example, lends perspective on single turbine engineering performance, while net capacity factor clearly shows total turbine (or wind farm) productivity after all losses and availability have been accounted for.

System-Level Characteristics

Turbine Characteristics: Figure 2 shows representative turbine and windfarm characteristics between 1995 and 2030. Turbine size is shown increasing from 300 kW in 1995 to 1 MW in 2005, remaining at this size through the latter years. Tower hub height is shown rising throughout the years, to 100 meters in 2030. This is indicative of a general trend toward taller towers. However, tower height is a site-specific choice and actual heights for turbines will probably be found on either side of those presented in the characterizations for any given year.

System Performance Characteristics: Performance gains are shown in Figure 2 in terms of capacity factor and net annual energy output per unit of rotor swept area. Net capacity factor increases substantially in the years 2000 and 2005, with less dramatic gains in the later years, from 26.2% in 1995 to 36.9% in 2030 (in a Class 4 wind regime). Changes in assumed losses reflect improvements in control losses and blade soiling losses in the early years, and array losses in 2005. Note that there is an attempt in the TC to differentiate between ridge and plain sites, since turbine siting and corresponding array losses will vary significantly. As an analytic convention, "plain" sites are assumed to be wind class 4 regimes, while, "ridge" sites are assumed to be class 5 and above. Although this does not precisely represent reality, the use of these two assumed sites allows a range of sites to be represented in analysis. Availability, having increased substantially over the last decade, is

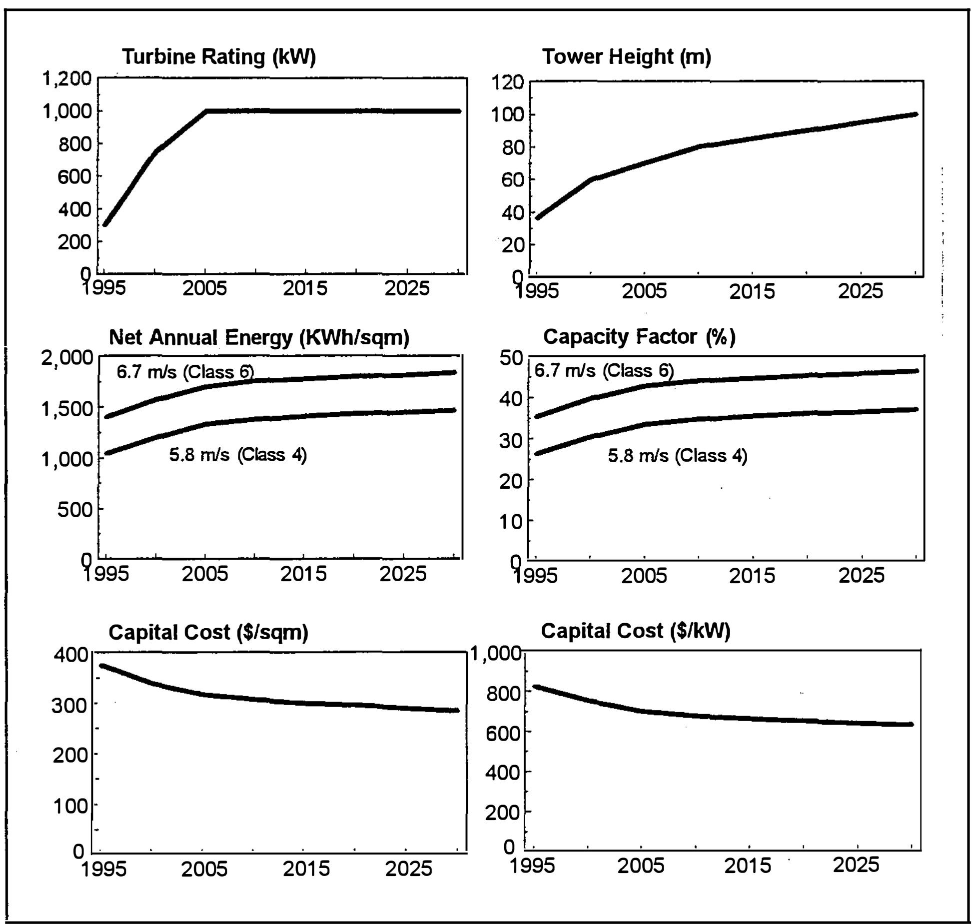

FIGURE 2. WINDFARM PROJECTED CHARACTERISTICS

characterized as level at 98%.

System Cost Characteristics: Installed farm cost numbers include turbine cost, shipping, installation and balance of station (grading, substation, engineering fees, etc). Costs are shown in Figure 2 moving from a current \$825/kW to \$625/kW in 2030. These reductions are influenced primarily by reductions in materials and eliminations in subsystems (geared transmission) in the near-term. In the long-term, the majority of weight (and therefore cost) reduction is assumed to have been extracted through improved design. The remaining gains therefore come from increased volume of production and improved manufacturing processes associated in part with the production volume increases. Although lower costs are not an inevitable result of higher sales volume, there are several specific volume effects that reasonably can be expected to lower turbine and windfarm costs in the future. First, increasing sales may allow a move to a new manufacturing technologies that lower production costs. Second, there is an established learning effect in similar products that indicates (logarithmically) decreasing product costs as cumulative sales increase. Third, as production volume increases, there is an opportunity for larger volume discounts on off-the-shelf components for turbines.[7]

Subsystem Performance Improvements

Estimates of performance for all years are formed using turbine energy output simulation software that takes into account overall system characteristics starting from rotor performance curves. This enables rapid evaluation of the effect on economics of changes in various subsystems. The C_p (coefficient of performance) curve for 1995, for instance, is modeled as a fixed speed, fixed pitch machine, while the 2000 turbine has a power curve typical of a variable speed machine (maintaining rated power above the rated wind speed). Generally, progression in rotor performance is characterized less by increases in peak C_p and more by maintenance of a relatively high C_p over a larger wind speed range. Additionally, a lower turbine cut-in speed is modeled as an advance in 2000 and beyond. Generator, transmission and power electronics performance (efficiency) are not explicitly modeled. Currently, these efficiencies are incorporated into the C_p curves used.

Tower heights increase throughout the projection period. This is not an indication that in the real world towers will gradually increase in height, but rather an indicator that the optimized system will trend toward higher towers, with specifics defined by the project site. Improvements in design software and general reductions in turbine weight per unit output will permit this shift in the optimum design point for turbine towers.

Other performance gains are reflected in changes in losses for turbines and farms. Blade soiling losses, specifically, are expected to be reduced early on. Array losses will be slightly reduced as micrositing software improves. Greater understanding of wind inflow characteristics and more sophisticated control algorithms should allow reductions in control losses.

Subsystem Cost Improvements

Table 1 summarizes the key qualitative assumptions driving subsystem cost improvements. The rotor subsystem is a significant cost driver. Cost increases (per kilowatt of generator rating) in the rotor subsystem are assumed for the years 2000 and 2005. The 2005 increase is due to the combined effects of a move to variable pitch blades and a significant increase in rotor diameter. (A percentage of blade cost tends to increase approximately with the cube of rotor diameter.) However, cost increases in 2005 are offset somewhat from improved manufacturing techniques resulting from the DOE/industry cost-shared Blade Manufacturing Project.

TABLE 1. ASSUMPTIONS FOR MAJOR SUBSYSTEM COST DRIVERS

	1995-2000	2000-2005	2005-2010	2010-2030
Rotor	Increase from larger size	Increase from size. Reduction from advanced manufacturing	Increase from size	Incremental reductions from lighter & smarter rotors
Tower	Largest increase from largest height increase	Decrease from smarter lighter, flexible top of tower system	Incremental increases with height (less than linear due to lighter components at top of tower)	
Generator	Induction - cheapest, off-the-shelf	Synchronous - a little higher cost	1st generation permanent magnet - highest cost	Incremental improvements in permanent magnet cost
Electrical	1st generation variable speed is expensive	Major cost drop as technology matures	Incremental improvements	
Drive Train	Direct drive - No transmission			
BOS	Incremental reductions from learning, maybe warranties			

Tower costs increase significantly in 2000, with incremental variations in the per kilowatt costs in out years. In the later years, cost per kilowatt increases at a rate lower than the tower height increases due to assumed advances in the ability to shed aerodynamic loads and design lighter turbine structures. Generator cost increases (per kW) up to 2005, as a result of moves to higher performance technologies. Sample technologies might be synchronous or doubly fed generators in 2000, and permanent magnet generators in 2005. Advances in manufacturing and design, and volume effects account for the cost decreases in the latter years.

Power and control electronics and other electrical costs show a significant increase in year 2000, as variable speed power electronics are used to enable direct drive to be implemented. Cost decreases through 2010 result from power electronics technology advances and, to some extent, increases in sales. Cost reductions in the latter years result primarily from volume effects. A major cost decrease in the transmission system is realized in 2000 as gearing is eliminated. This more than offsets the higher electronics, tower and rotor costs experienced during the same period.

MARKET CHANGES AND DOE COST GOALS

The domestic market for wind energy has changed dramatically and continues to change, presenting a serious challenge for the wind energy industry. Five years ago, after a decade of substantial wind progress and with natural gas prices seen as heading toward $4.00 per MMBtu by 2000, wind energy looked like a likely candidate for utility/Independent Power Producer (IPP) use as a fuel saving technology. Now, although the technology continues to progress steadily and recent international turbine deployment has been substantial, installation of large scale windfarms has stalled domestically, due to the confluence of low fossil fuel prices, utility restructuring and continuing improvements in natural gas-fired turbine efficiencies. With an increasing emphasis on spot market purchases (at less than 2 cents/kWh in many cases) and a trend toward natural gas combined cycle installations on those occasions where new facilities are needed, current wind installations tend to be fewer, smaller, and based on benefits other than cost. "Value," not "cost," will continue to be a key determinant of market success.

Cost of Energy Projections

The highest level and most commonly used figure of merit is levelized cost of energy (COE), expressed in cents per kilowatt-hour. This is a useful metric as it combines both elements of cost and performance and is recognized outside of the wind industry. COE figures used by DOE, however, have often differed from the (wide-ranging) numbers quoted for wind industry installations and project bids. It is important to point out that these apparent discrepancies have stemmed not from fundamentally differing opinions concerning the state of technology, but rather primarily from different financing and wind resource assumptions. For instance, current market projects and bids usually include federal renewable energy production incentives (REPI) or tax credits, depending on whether the project is for supply to investor-owned or municipally-owned utilities, respectively. DOE's COE figures do not include these incentives. Also, financial aspects may vary widely for different projects.

Another common difference between market and DOE Technology Characterization numbers is that DOE quotes COE in constant dollars because of the ease of use for technology tracking and in economic modeling (such as the national energy modeling performed by the Energy Information Administration). In contrast, bids and contracts are in current dollars, which appear higher than constant dollar figures.

DOE has historically quoted COE for Class 4 winds, in line with DOE goals to help make wind energy economically competitive in these regimes. Industry installations have tended to be at higher wind sites, with consequent confusion over "real" costs of wind energy. Although near-term wind installations will continue to target good wind resource sites, in order for wind to contribute large amounts of electricity to the nation's supply, opportunities in regions of the U.S. that have lower wind resources must also become economic by improving the technology. Figure 3 indicates the relative quantities of wind resource in various regimes, emphasizing the tremendous depth of the Class 4 resource.[8] Note, however, that current turbine deployments still use only a fraction of the available Class 5 and 6 lands.

The current Technology Characterizations partially address these issues and the changing nature of the marketplace by presenting a matrix of COE's, corresponding to various combinations of wind regimes and ownership/financing structures and using the cost and performance numbers from the TC. Figure 4 shows COEs from this matrix for year 2000 and 2030. It is important to note that these COE values are draft numbers and are subject to small changes as work is completed later this summer. The range of COEs is representative of different potential markets that are emerging as market restructuring continues.

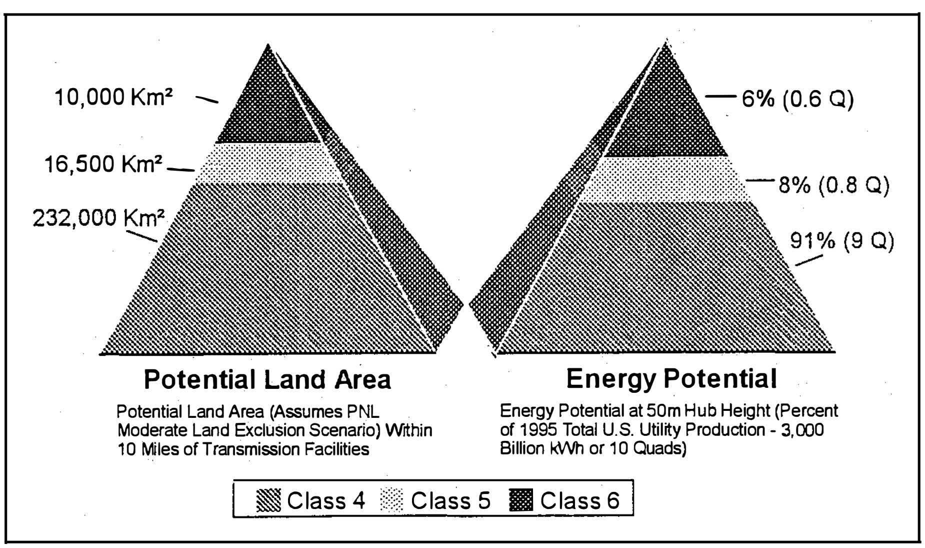

FIGURE 3. AVAILABLE WIND RESOURCE

COE figures were obtained using cash flow modeling with realistic financing and tax assumptions for the different scenarios. Investor Owned Utility (IOU) and Municipally- or publicly-owned ownership cases (MUNI) use the cost-based revenue requirements method to figure COE, while Independent Power Producer (IPP) Ownership uses a market-based Discounted Cash Flow-Return On Investment (DCF-ROI) method. The MUNI projects are most advantageous to wind because financing is 100 percent tax-free debt (no expensive equity) over the plant lifetime, assumed to be 30 years. MUNIs also pay no income or property taxes. IOU is next costly, financed with 50 percent debt and 50 percent equity over the plant life (again, 30 years). IPPs use project financing which retires debt over the shortest period (for example, 15 years), and uses more debt financing than IOUs, but with a much higher equity rate. Together, these characteristics make IPP the highest cost form of financing. A more detailed discussion of financial assumptions can be found in the 1996 Technology Characterization.

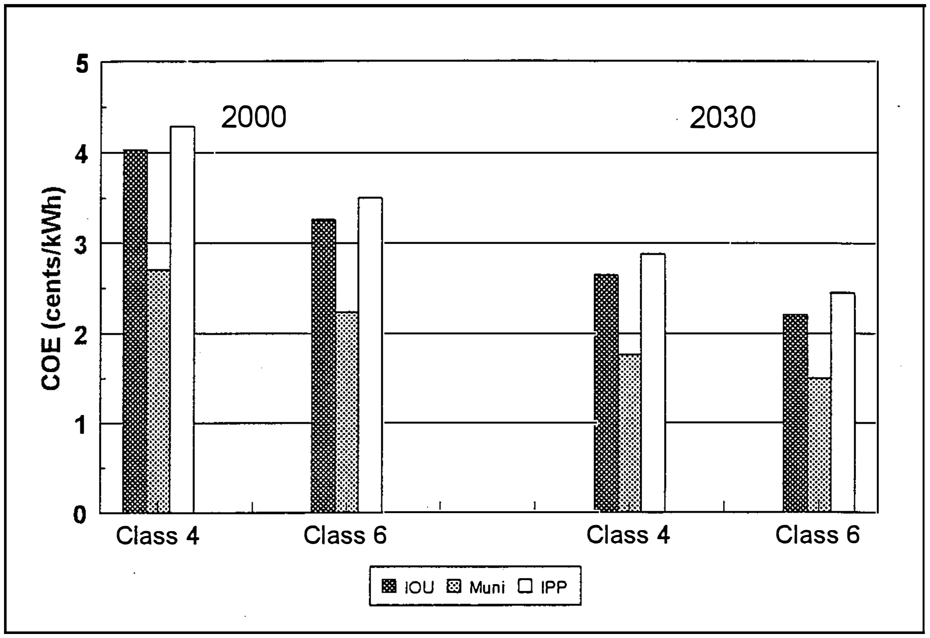

FIGURE 4. FINANCING AND RESOURCE IMPACTS ON COE

The figure shows that COEs for the same technology could conceivably range from a low of about \$0.023/kWh (Muni, class 6) to a high of about \$0.043/kWh (IPP, class 4) in year 2000. Obviously, the resource and ownership/financing structure have a large effect on the COE. How well these COEs will enable a specific wind project to compete will depend on the payment the windfarm developer/owner can collect plus any additional value of the windfarm, as perceived by the utility and its customers. In fact, a windfarm with a higher COE may be competitive in some locations while one with a lower COE is not competitive in others.

MARKET WILL EMPHASIZE VALUE

The Technology Characterizations put a heavy emphasis on cost of energy to evaluate progress and viability of individual renewable electric generating technologies, and to compare technologies against each other. However, as a key determinant of market success, value issues ("what is it worth" versus "what it costs") are particularly important to examine and, if possible, quantify in this difficult market environment. Table 2 lists some of these cost and value factors. Other papers presented in this conference session detail recent DOE efforts to analyze certain factors listed in the table.[9,10]

In arenas where values beyond short-term price are recognized, wind power is currently being adopted. For example, in Minnesota, a regulatory mandate reflecting public preferences and non-monetary values, combined with a good wind resource area and utilization of the federal production credit has resulted in an independent power project with levelized purchase prices of around 3 cents/kWh. For the near-term market, wind energy will need to continue to exploit niches where additional value is reflected. In addition to treatment of value, other characteristics make for suitable wind customers. Low cost of

TABLE 2. MARKET SUCCESS DETERMINANTS

Cost Factors	Value Factors
Technology performance, capital and operating costs	Capacity and energy avoided costs
Wind resource quality	Price certainty (i.e., no fuel escalation risk)
Financing	Generation mix diversity
Taxes	Environmental impacts
Policy incentives	Modularity, short lead times
Project ownership	Economic development
Permitting processes	Regulatory directives
Land cost/lease/royalty terms	Public preferences
Transmission (construction/upgrades and access/wheeling)	Distributed utility value

financing is a particularly desirable characteristic for capital-intensive technologies such as wind. Publicly owned utilities, with their access to favorable financing, their responsiveness to customers, and a less cumbersome regulatory environment, are likely candidates for wind development. Other examples of potential markets are cooperatives, power marketers, renewable power aggregators and direct access customers. The Federal Wind Program will continue to work to increase the understanding and recognition of various aspects of value to utilities and their customers. Specifically, DOE is looking forward to working closely with National Wind Coordinating Council (NWCC) members and others to identify near-term market openings and to help package wind for these opportunities.

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