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ABSTRACT

This paper identifies two possible wind turbine system architectures that represent the next generation of horizontal-axis designs, targeted for the mid-1990s. Estimates of the effects of projected design refinements on energy capture and cost are used to calculate cost-of-energy (COE) estimates. Two basic design philosophies are presented: the first represents a system using power electronics to allow variable speed operation and the second represents an optimized stall-controlled rotor. Both concepts take advantage of recent technological innovations including advanced airfoils; innovative control strategies; drive-train improvements; and site-dependent system optimization strategies, such as tall towers for sites with strong vertical wind shears. Our investigation indicates that these design improvements will increase energy capture about 40% to 50% with a corresponding negligible impact on cost, when compared with current state-of-the-art wind systems. These performance improvements result in COE estimates ranging between $0.03 and $0.06/kWh for the mid-1990s for sites with annual average hub-height wind speeds from 8.5 mps to 6.8 mps.

INTRODUCTION

Although the levelized COE from wind turbines has dropped dramatically since the 1970s, further reductions in COE are necessary for wind generated electricity to be economically competitive for utility applications at moderate wind-speed sites. Over the next five years, it is expected that wind technology will mature significantly over current designs, as industry incorporates the lessons learned from operating experience gained in the California wind farms. This experience, combined with recent results and analytical tools developed by the U. S. Department of Energy's research program, will be used to develop optimized, matured wind turbine technology that will be competitive with conventional electricity generation at good wind sites. A likely course for future wind turbine development will be an incremental evolution from the current technology in the near term (the mid-1990s) toward more advanced technology in the longer term (post-2000). We present some insight into the possible configurations for some of the more promising near-term design options and the resulting projection of improvements to performance and cost. The effects of these design changes on performance, durability, system cost, and operation and maintenance (O&M) cost are analyzed by comparing estimated COEs from matured systems with corresponding current, or baseline, designs. Some of the more radical design changes expected for the advanced turbine technology in the longer term are not yet well enough defined for in-depth analysis, but several research opportunity areas will be addressed in this paper.

We have identified a baseline design representing the current state-of-the-art horizontal-axis wind turbine. COE estimates for this baseline design are presented for several different wind sites to provide reference points to examine the effects of design improvements. COE estimates are also made for two near-term improved designs based on performance and cost improvements with respect to the baseline. We were very fortunate to receive the cooperation of several industry members who shared their opinions regarding near-term improvements to existing designs. Their input was used to provide a reasonableness check for our COE projections. COE projections for the far-term concepts are also presented, with the understanding that the uncertainty bands associated with the assumptions for cost and performance are necessarily large.

APPROACH

The general approach used to determine the effects of design improvements on delivered COE can be described by three basic steps. First, the baseline wind turbine system was selected and its performance and costs were tabulated. Second, two configurations representing possible near-term improvements to the baseline design were identified, and the effect of each improvement on performance and cost was estimated. Last, the chosen figure of merit, COE, was calculated for the baseline and improved designs. The performance and resulting COE were determined for four different wind regimes to determine the sensitivity of COE to the available resource.

The baseline design is representative of a currently deployed wind turbine, rated at 200 kW, and the wind data used for the performance analysis represent four relatively good sites. Figure 1 shows the wind-speed distribution curves that we used. The data shown on these plots has been adjusted to a height of 90 ft, which is the assumed hub height for the baseline turbine design. Three of the curves were derived from measured data representing different types of terrain and weather patterns from various locations across the United States, and the fourth curve represents a Rayleigh wind-speed distribution typical of the vast resource in the Great Plains. The average annual wind speed at 90 ft for each site is as follows: 6.5 mps for Altamont Pass, California, 8.2 mps for Bushland, Texas, 8.5 mps for San Gorgonio, California, and 6.8 mps for the Rayleigh site.

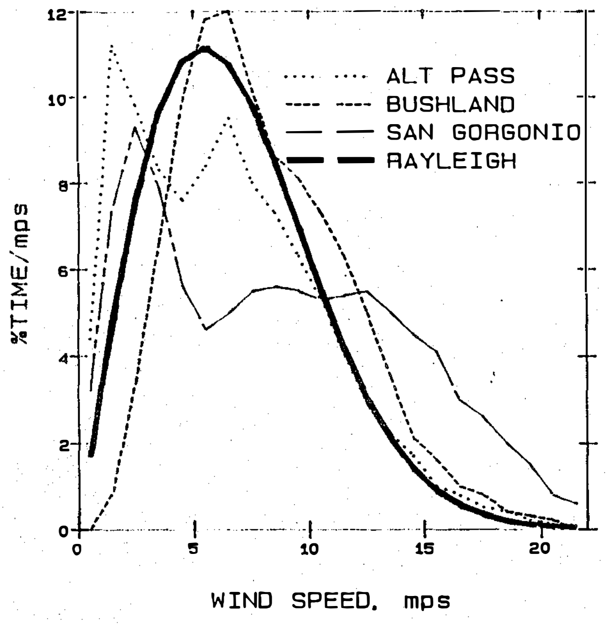

Figure 1. Wind Speed Distributions at 90 ft.

Energy capture estimates for the baseline design were derived from the power curve shown in Figure 2 and the four wind-speed distributions. The method and economic assumptions used to compute the COE are documented in detail in reference [1]. The COE calculation is taken directly from the Electric Power Research Institute Technical Assessment Guide [2], which is the method most utilities use to assess the costs of generating electricity. Table 1 summarizes the assumptions used in the COE calculations for operation at each of the selected sites for the baseline design. The resulting values for COE from the baseline design ranges between $0.05 and $0.08/kWh, depending on the wind regime.

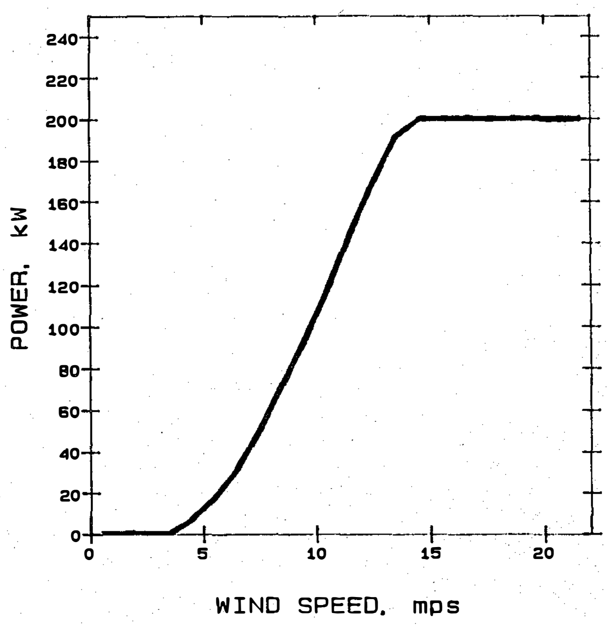

Figure 2. Power Curve for the Baseline Design

Table 1. Economic Assumptions for the Baseline Design

System cost	$210,000
Annual gross energy capture	330-550 kWh
Discount rate (constant dollar)	0.061
Fixed charge rate	0.102
Availability	95%
All losses	23%
O&M costs	$0.010/kWh
Replacement costs (8th year)	$30,000
Replacement costs (20th year)	$30,000
Present value factors	8th yr: 0.6227, 20th yr: 0.306
Capital recovery factor	0.073
Book life	30 years
All costs	1989 constant dollars

NEAR-TERM IMPROVEMENTS

Two general configurations were chosen to represent possible near-term improvements to the baseline design. Fatigue life and reliability have been identified as key problems with existing designs, so both of the systems discussed here address these issues. The first concept incorporates a variable-speed rotor, using power electronics to provide constant frequency line current. It also uses advanced control systems to take full advantage of different wind characteristics and advanced airfoils for increased power output and reduced loads. The drive train and the rotor hub will incorporate optimized designs leading to reduced loading. We also envision taking advantage of vertical wind shears by mounting the turbine atop a considerably taller tower, which will be optimized for the site.

The second concept is a stall-controlled rotor, using passive aerodynamics to limit maximum power output. This concept would also take advantage of the other advances previously mentioned, including advanced control systems, advanced airfoils, improved rotor and drive train designs, and the taller tower.

Table 2 lists the expected impact of improvements in general analytic and design capabilities, as well as specific hardware advances for the two concepts. The improvements are given as percentages relative to the baseline design assumptions for system cost, annual energy capture, and annual O&M costs. For instance, for a variable-speed turbine design, the Solar Energy Research Institute (SERI) Concept 1, the cost improvement from application of the structural codes is a positive 5% of the baseline (cost is reduced 5% of the baseline total cost). No change in energy is projected due to the use of this tool. As another example, note that the "Control Systems" actually raise the system cost by a small amount (the amount is shown as a negative percent improvement) This brings the net cumulative change in cost back up toward the original cost. The cumulative total increase in energy production from all technology improvements to SERI Concept 1 is 56% (1.56 x baseline energy), although there is no net change in cost from these same improvements. For the stall-regulated turbine design, SERI Concept 2, a total cumulative increase in energy of 49% and a decrease in cost of 12% are projected.

Table 2. Performance and Cost Estimates for (1995) SERI Concepts 1 and 2

Technical Advances	% Improvement System Cost	% Improvement Energy Capture	Improvement in Annual O&M (cents/kWh)
<u>Codes</u>			
Structural	5%	--	--
Fatigue	5%	--	--
Micrositing	0%	6%	--
<u>SERI Concept 1 - Variable Speed</u>			
Power electronics	-10%	10%	.00
Control systems	-1%	5%	.20
Advanced airfoils	0%	10%	.10
Drive train	4%	--	.10
Tower (tall)	-8%	25%	.01
Rotor hub	5%	--	.10
Total	0%	56%	.51
<u>SERI Concept 2 - Stall Controlled</u>			
Aerodynamic controls	2%	3%	
Control systems	-1%	5%	.15
Advanced airfoils (Rotor design)	2%	10%	.15
Drive train	2%	--	.10
Tower (tail)	-8%	25%	.01
Rotor hub	5%	--	.10
Total	12%	49%	.61

A brief discussion of projected key impacts for each design follows.

<u>Common to Concepts 1 and 2</u>

<u>Structural Codes</u> - By enabling designers to incorporate better understanding (developed by program research and development [R&D]) of the loads felt by the rotor, predictive structural analysis codes will allow them to optimize designs, thereby saving cost on materials. Cost savings on the order of 5% are predicted by researchers. There are several reasons why the 5% estimate is conservative. First, it does not account for any gains in "manufacturability." It is simply an estimate of cost reduction through advances in design capability. Industry has proved that, given advances in the technical base, it is able to bring costs down significantly.

Second, recent research indicates that the estimated percentage is well within reason. One paper from SERI [3] indicates that field tests have confirmed FLAP (Force and Loads Analysis Program) model predictions that teetered, flexible rotor designs show greatly reduced loading compared with rigid hub, stiff rotor designs. From field tests performed in cooperation with Industry, the normalized deterministic flapwise bending moments for the first two harmonics of the rotor were found to be generally one-half as much for the flexible design. In addition, the variances of the random blade root bending moments for the rigid design were an order of magnitude larger than for the flexible design. These results agree with FLAP code predictions, showing the importance of designing the rotor blades to produce natural frequencies that are not coincident with rotor passage frequencies. Loads felt by the turbine tower were also analyzed for the industry turbines. Understanding how to minimize such loads will lead to reductions in material for the tower and other structural components. Again, test results showed that the energy content in the harmonics of the stiff system were higher than for the flexible system. Thus, it has been demonstrated that predictive structural design tools will be able to be used to more accurately optimize rotor design and turbine operation to control the harmful loading experienced by the wind energy system.

Fatigue Codes - Use of fatigue life prediction design codes will reduce installed cost because it will enable manufacturers to design within tighter margins and maintain fatigue life goals. In addition, a reduction in component replacement costs, resulting from a longer lifetime, will be possible. A reduction of approximately 5% of cost is estimated for both concepts. (The combined benefit on cost of using predictive structural and fatigue codes is 10%.)

A recent analysis by researchers at Sandia National Laboratories [4] indicates that such reductions in design margin are easily achievable with the use of fatigue analysis/lifetime prediction tools. Using the newly developed LIFE-2 code, the analysis compares rotor blade lifetime calculations using design-condition inputs to those made with measured-condition estimates from the 34-m vertical-axis wind turbine (VAWT) test program. It found that estimates using the design conditions consistently underestimated service lives for all operating modes investigated. Because service lifetime was found to be very sensitive to the various lifetime calculation input parameters, a small increase in the confidence of predicting the lifetime calculation input parameters will translate into a significant increase in the confidence of service lifetime prediction and, concurrently, a decrease in the necessary design margin. Therefore, if designers could have more confidence in the accuracy of the input parameters, they would be able to decrease current design margins.

There are numerous examples of recent progress made by the program in increasing the confidence in predicting the various Input parameters. For instance, advances in wind prospecting instrumentation calibration techniques [5] and in theoretical characterization of the incoming wind field [6] have increased the ability both to predict the resource on the larger scale of the array and to describe the wind Input on the smaller turbine rotor scale. Predictions of mode shapes and frequencies for the 34-m VAWT test bed were shown to be within 5% of observed values for a wide range of blades modes [7]. Combined, these advances will enable Industry to easily meet the 5% cost reduction estimate.

Micrositing - Improved energy capture of about 5 to 10% is possible by locating turbines to avoid losses from wake interactions and to take advantage of terrain-induced effects. Other possible benefits include lowering fatigue loads by avoiding local high-turbulence zones. Based on recent studies Investigating such effects, researchers feel that Increasing energy by 5% to 10% Is well within the range of achievable Improvements. Several studies have shown wake energy deficits to be between 20% and 30% and even as high as 40% In the Altamont Pass region [8, 9].

Using results from array wake measurements taken under the Cooperative Test Program in the mid-late 1980s, researchers at Pacific Northwest Laboratory (PNL) estimate that they were able to predict array deficit uncertainty to within 25% to 30% accuracy. The most recent work at PNL involving a comprehensive summary of wake/array loss R&D results should allow estimates to be made with better than 20% accuracy. A recent analysis of field data from turbines at the Goodnoe Hills site in Washington concluded that reductions in wind speed of 30% and increases in turbulence by a factor of 2 to 3 were present at locations up to 500 meters from up-wind clusters of trees [10]. Another study estimates that of the 50% energy shortfall between predicted and actual values for all wind plants in California in 1985, 13% was from siting/array losses and 34% was from wind resource overestimates [11]. Combined, these studies indicate that a 5% to 10% increase in energy capture resulting from a better understanding of micrositing phenomena is quite realistic.

Advanced Airfoils - Substantial analytical work and field testing of a new family of thin airfoils at SERI indicate that energy capture increases of 10% have already been exceeded [12]. Incorporating these new airfoils in the next generation of advanced turbines imposes no technical problems. Even greater gains in energy capture were demonstrated by researchers at Sandia using test results from the 34-m VAWT test bed to confirm projected improvements from airfoils designed specifically for VAWTs [13, 14]. These papers confirm earlier theoretical predictions that reductions in wind turbine cost of electricity on the order of 25% are possible from the application of natural laminar-flow blades [15].

Drive Trains - Integrated drive-train designs specifically for wind turbines could reduce system costs by about 5%. The most detailed study of integrated drive train designs was made by the U.S. Windpower and utility consortium which Is presently developing a new turbine [16]. This paper describes an integrated hub/drive train/mainframe.

Structurally Tailored Towers - Use of stronger, lightweight materials and new design techniques to tailor towers to sites to take advantage of wind shear and local terrain effects can increase energy production. Obviously, impacts on energy capture and costs will vary depending on the specific design. This analysis assumes that an increase in height from 90 to 180 ft yields between 20% and 30% more energy (using the "1/7 power law" to scale wind speed) with only a 10% cost penalty. (In the table, note that energy capture increases, but so does cost.)

Rotor Hub - New rotor hub designs would be optimized to reduce rotor loads by providing increased flexibility. Techniques might include hinged blades, or teetered or gimbaled hubs that allow motion in three directions. These improved designs would take advantage of new materials and are estimated to reduce system costs approximately 5% to 10%. Field test data comparing loads between teetered and fixed hubs verify the reduction in rotor loads associated with flexible hubs [3].

Specific to Concept 1

Power Electronics - Preliminary R&D by the program shows the potential improvement In energy capture from variable speed, constant-frequency operation to be on the same order of magnitude as the Increase in cost -- near 10% [13, 16]. The design tradeoff study performed for the current U.S. Windpower/utility turbine development program agrees with this analysis [17]. A key risk associated with the variable-speed design is that the rotor speed can coincide with one of the many mechanical resonant vibrational frequencies of the wind turbine, leading to severe material fatigue damage. With proper control, however, these resonances can be avoided.

Even if the cost/energy tradeoff experienced with the variable speed design comes out basically even, the added benefit of reducing fatigue loads by avoiding severe operating conditions, smoothing peak power control, and absorbing energy from wind gusts may be enough of a reason to justify its use. Again, the industry/utility study agrees with this conclusion, adding that power electronics will have a favorable impact on power factor control and will help reduce power fluctuations [17]. This paper also states that Industry expects power electronic controls (for variable-speed systems) to decrease in cost as the technology matures.

Control Systems - Advanced control systems that not only take advantage of the variable-speed capability, but also adapt to local wind resource characteristics, would increase energy capture by about 5% and minimize damaging fatigue loads. Although the control system cost itself would increase significantly, the increase of the total wind turbine system cost would only be about 1%. A recent study by W. A. Vachon and Associates describes a model that simulates variable-speed operation, assessing overall impact on life and energy production for numerous control strategies [18]. Using the variable-speed controller described in the paper significantly reduces the amount of time the turbine spends operating in a critical speed range, which consequently reduces the cumulative fatigue experienced by the turbine.

Specific to Concept 2

Aerodynamic Control Systems - An essential control function for a stall controlled design is the capability for reliable aerodynamic braking to provide fail-safe operation in high winds. The capability to adapt operation to local wind resource characteristics results in an approximately 3% increase in energy at a total system cost increase of 1%.

Our preliminary estimates of the advantages of these concepts indicate that for Concept 1, the overall system installed cost will not be affected, but the annual energy output will be increased by 56% and the annual O&M costs will be reduced by about $0.005/kWh. For Concept 2, the installed system cost will be reduced by 12% and the annual energy output will be increased by 49%, with a $0.006/kWh reduction in annual O&M costs. Table 3 summarizes the energy capture, capital cost, and annual O&M and retrofit costs for the baseline and advanced designs. Note that the annualized costs listed for major retrofits include two retrofits for the baseline in years 8 and 20, and for SERI Concepts 1 and 2, only one retrofit is assumed to occur in year 20.

The net effect of these design improvements is reflected in the COE estimates, as shown in Figure 3. The baseline COE estimates are shown for reference, and the points labeled S-1 and S-2 represent the estimates for SERI Concept 1 and SERI Concept 2, when operating in each of the four wind-speed distributions.

The COE estimates for the baseline range between $0.05 and $0.08/kWh, depending on the wind regime. The COE estimates for the two SERI mature designs are, for all practical purposes, identical, with a range of $0.03 to $0.05/kWh. The trend lines indicate the likely range for the future cost of energy from wind turbines for sites with average (measured at 90 ft) wind speeds between 6.8 and 8.5 mps, given our performance and cost assumptions.

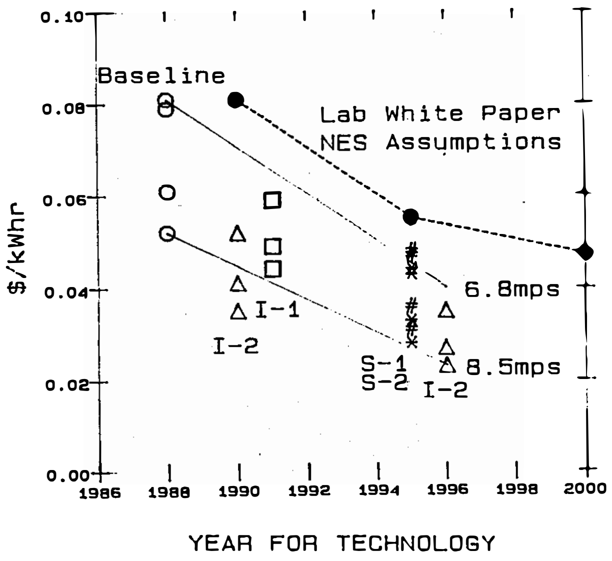

Figure 3. COE Estimates as a Function of Hub Height (90 ft) Wind Speeds and Technology Development

Also shown in Figure 3 are the COE estimates from two industry members. The I-1 design is targeted for employment in 1991 and reflects the performance and cost projections of one company. Our economic analysis of their inputs provided the COE estimates shown of between $0.04 and $0.06/kWh for 1991. The second company to offer their estimates, I-2, provided us with projections for two different

Table 3. Energy Capture and Cost Assumptions

					Net Annual Energy (kWh/yr x 10^3)			
Year	Concept (Rating, kW)	Capital Cost, ($)	Annual O&M ($/kWh)	Retrofits ($/kWh)	Alt. Pass	Bushland	San Gorgonio	Great Plains
1988	Baseline (200 kW)	210,000	0.010	0.006	330	460	550	340
1995	SERI-1 (200 kW)	210,000	0.005	0.002	510	720	860	530
1995	SERI-2 (200 kW)	185,000	0.004	0.002	490	680	820	500
1991	I-1 (300 kW)	300,000	0.022	*	710	980	1,170	720
1990	I-2 (200 kW)	116,000	0.015	0.001	330	470	600	340
1996	I-2 (200 kW)	125,000	0.008	.001	480	670	850	480

*The O&M for I-1 includes amortization for major retrofits.

designs that could be employed in 1990 and 1996. Our results indicate that their COEs would range between $0.035 and $0.055/kWh for 1990, and between $0.02 and $0.04/kWh for 1996. Although neither of these industry designs is yet in production, they do provide us with an independent comparison to the SERI estimates. All the projections agree reasonably well over the study time horizon and indicate that there Is a consensus on the future COE trend.

Note that two of the wind speed distributions used for this analysis represent outstanding wind resources, and they have limited land areas associated with them. Although these sites are important to gain market entry by assuring lower COEs, they cannot generally be counted on for large-scale implementation of wind energy. The more typical sites are represented by the Altamont Pass and the Rayleigh distribution. The dashed line in Figure 3 shows the COE estimates that were used for the recent interlaboratory white paper [19] in support of the Department of Energy's National Energy Strategy (NES). The assumptions used to derive these COE estimates include a 13-mph (measured at 30 ft) Rayleigh wind-speed distribution and an accelerated R&D program to support the design and development of a near-term concept. Another important assumption used with the NES projections concerns large-scale market implementation. There is a 5-yr time lag imposed between the year the technology is available and the year that it enjoys widespread acceptance. Thus, the NES estimates appear conservative in relation to the results from this analysis.

Far-Term Concepts

The innovations required to carry wind energy technology into the 21st century are not well defined at the present. The long-term technology development depends on many factors, including innovations in related fields, such as materials science and power electronics, as well as funding levels for the Wind Program R&D. The Wind Program has identified many areas for technical advances that hold potential to further increase the economic competitiveness of wind energy, some of which are common to the near-term advances already discussed. Examples of high-potential Improvements include:

- Advanced airfoil families designed specifically for wind turbines to increase performance and reduce load
- Variable speed drives or generators to allow the rotor to operate at optimal speeds over a wide range of wind speeds
- Adaptive, or smart, controls that adjust system operating parameters based on the wind characteristics
- New hub configurations that allow for greater flexibility and thus reduce loads and increase lifetimes
- The incorporation of advanced materials to allow the manufacturing of lighter, stronger components
- The development of a damage-tolerant rotor, adapting aerospace techniques in the use of composite structures
- A better understanding of micrositing effects on wind characteristics, such as turbulence and wind shear, can allow for the optimal placement of individual turbines in complex terrain or large arrays to significantly increase performance. This is required for design decisions as well - for instance, regarding the optimum tower height for each site.

Most of the improvements identified for the near-term, mid-1990s design were focused on improving energy capture with minimal cost impact. The advances we envision for the far-term, post-2000s designs have a much more significant cost impact. For instance, referring again to the Interlaboratory White Paper [19], the capital cost decreases from $1100/kW in 1990 to $1000/kW in 1995 to $850/kW in 2010. Annual O&M costs (including retrofits) decrease significantly as well, from $0.017 to $0.013 to $0.008, for the same years. Most of these cost decreases can be achieved through improved design practices leading to lighter, more structurally sound and reliable systems.

The effect on COE of all of these Incremental improvements is projected to be a reduction to about 40% to 50% of current levels, or between $0.03 and $0.04/kWh for a typical Great Plains site, with a Rayleigh wind-speed distribution targeted for the post-2000 time frame.

CONCLUSIONS

The design improvements that will most likely be included in the next generation of wind energy systems are fairly well defined. Their cumulative impact will be to reduce the delivered cost of energy to about $0.05/kWh for a typical wind regime such as that found on the Great Plains.

The impact of further design improvements required for the far term, post-2000, is much more difficult to quantify at this time. However, current estimates for cost of energy in the post-2000 time frame are between $0.03 and $0.04/kWh for the same Great Plains wind regime. COEs in this range would make wind energy very attractive for large-scale penetration into our nation's electricity supply mix.

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