OVERVIEW OF WIND TECHNOLOGIES

Introduction

The objective of this Technology Characterization (TC) is to summarize the likely cost and performance improvements in wind technology used for a domestic large windfarm application. Major improvements in cost and performance of wind turbines are likely in the future. Considerable operating experience has been gained over the last 15 years from domestic windfarms, primarily in California but also in Minnesota, Hawaii, Texas, and Vermont. Advances have been made in the ability to design, site, install, operate, and maintain turbines, both on a single-unit level as well as part of an entire windfarm. These improvements are the result of work in manufacturing facilities, windfarms, and research laboratories, and are due to improved manufacturing methods, operating experience, and government and industry research and development. The performance and cost improvements achieved by the industry are the prime reasons for current market acceptance on a limited basis. Still, uncertainty exists in the minds of many would-be investors and utilities, and private developers have indicated that their projects include a cost premium that reflects a perceived higher risk compared to more mature generation technologies.

Technology Assumptions

The turbines characterized in this document are a composite of several different designs, each of which represents a technology likely to be purchased by users at the present time or in the future. For example, the 1997 technology description is most highly influenced by the 3-bladed, rigid hub, relatively heavy designs of Eurpoean origin which have been typical in the 1990s. These include the Zond 550 series, and several commercial European turbines. The 1997 description also incorporates the lightweight, more flexible U.S. designs, which have been under development by manufacturers, some in conjunction with the DOE Near-Term Product Improvement Project. Such technology is best represented by three machines: the AWT-26/27, the North Wind 250, and the Cannon Wind Eagle 300. The year 2000 description is a composite drawing heavily from the current DOE Innovative Subsystem Project, and from conceptual design studies and preliminary prototype design plans developed under DOE's Next Generation Turbine Development (NGTD) Project. It assumes a variable speed generator, larger rotor and advanced airfoils, higher hub heights and advanced control systems. The 2005 technology is a projection of trends as envisioned by R&D investigations of advanced components and by analyses conducted under the DOE Wind Energy Program.

From a technology development perspective, the specific technology characteristics for each time period in this document are less important than the trend. The marketplace determines preferred technologies and designs as well as pricing strategies. European designers are as aware as U.S. designers of the design tradeoffs and opportunities for cost and performance improvement. Major government-sponsored advanced turbine development programs are underway in Europe. Often, European designs are larger (in the MW range) than corresponding U.S. designs. This appears to be due to the choice of the designer and the scarcity of European sites with good wind resources. Private sector-developed turbines in Europe are often in the 500 to 750 kW range described for 1997 and 2000 in this Technology Characterization. This TC does not project that all new wind turbines in 2005 will suddenly be a size of one megawatt. Some will be larger; some smaller. Rather, the TC projects a trend toward larger rotors, and higher hub heights and rated power. The choice of these parameters is up to the designer and the marketplace. Economies of scale, manufacturing volume and maintenance all interact. The trend in the United States has been to make design changes in increments and to gather experience with one size before scaling up. That trend is expected to continue.

Finally, this TC will describe cost and performance for relatively large 25 to 50 MW_e wind farms. An alternative is "clusters," which are typically sized at less than 10 MW_e. Several such installations have been built recently or are being developed in the U.S. under DOE's Turbine Verification Program in Iowa, Nebraska, New York, Oklahoma, Texas, and Vermont. Cluster plants may have somewhat higher installation costs and O&M expenses than shown here. Another option is small-sized (10 to 150 kW) turbines, which can be sited either individually or grouped, for rural or village power applications. Such plants also show different construction and O&M expense than described here. TCs for these two other wind plant types may be developed in the next few years.

Utility Integration Issues

In the near-future, it is likely that wind energy's primary market will be niches that recognize values in addition to cost. Nonetheless, the primary economic product from wind energy is electricity, and as such, a primary market is the electric power generation industry. Barring large policy changes, such as a carbon tax, the principal value of wind energy as an electric generator, without storage facilities, is as a fuel saver. That is, wind energy generation must be used when it is available, thereby displacing energy (and variable operating expenses) that would have otherwise been provided by conventional generation. Because of its intermittent nature, any additional value of wind-generated electricity beyond fuel savings and variable operating expenses will vary depending on (1) site-specific characteristics of the wind resource, and (2) utility load and other characteristics of the electric distribution system. For instance, the ability to site windpower closer to the end user (a "distributed" application) may increase its value to the utility.

Statistically, a windfarm can displace a fraction of the capital cost of some new conventional plant. The critical question, which depends on the correlation of the wind resource with utility demand, is: "How much capacity does a windfarm displace and how much is it worth?" This analytical issue is often termed the capacity credit issue, and can be characterized as firm, dispatchable capacity vs. any as-delevered capacity. Although capacity credit for wind energy is often not accepted by electric utilities, research by NREL [1], Grubb and Halberg in Europe, [2,3], and Henry Kelley at the Office of Technology Assessment suggests that virtually any wind installation merits a capacity credit. As an alternative, hybrid wind/gas or wind/storage systems could earn full capacity credit.

The annual energy generated from the wind can be estimated with some certainty, on a long-term basis. In addition, some locations can have a degree of predictability on a daily or hourly basis. These include islands with trade winds or sites such as the California passes, where winds are caused by the predictable inrush of cooler coastal air as the mountain desert air is warmed and rises. Thus, it is possible for windfarms to get some capacity credit in these locations. Based on these examples, utility operation and wind valuation are affected by wind forecasting ability. Researchers in wind prediction are now beginning to explore techniques which would allow the utility dispatcher to gauge the availability of his wind power plant over the next 6 to 36 hours. In the future, the ability to predict winds on relatively longer time scales will improve, potentially allowing windfarms to be operated with greater certainty, thereby increasing their value. Due to the regional variations in the amount and levels of the wind power resource, and to the other regional variations determining the competitive market for power generation, wind technology will achieve different levels of regional market penetration.

Analysts often quote penetration limits for wind capacity of 5 to 20 percent of installed conventional capacity [4]. This is based on a combination of longer-term system integration limits, such as those discussed above, and system operational limits on the second-to-hour time scale, such as generation control, load following, unit commitment, reserve requirement, and system voltage regulation. A recent study by NREL indicates that hardware and system design advances can address most of the technical concerns resulting from interfacing intermittent renewable generation technologies with the electric system [5]. U.S. studies have shown that a 5 percent penetration level has virtually no effect on system operations, while estimates of the impact of larger numbers appear to be largely speculative. Other work by Grubb and Halberg [2,3] in Europe confirmed that no absolute physical limit exists to the fraction of wind penetration on a large power system. Rather, with increasing penetration, the fuel and capacity savings begin to decrease, so that the system limits are economic rather than physical. Regardless, as Grubb points out, the penetration of wind energy in the U.S. must be much larger before its value begins to degrade in the electric system.

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Resource/Land Use

Wind energy resources are widespread in the continental U.S., Hawaii, and Alaska. The wind resource is very large with an accessible resource base of nearly 88 Quadrillion BTU, from sites with average wind speeds above 5.6 m/s (12.5 mph) at a 10 meter height [6]. Table 1 shows how energy production varies by wind class, and illustrates the critical relationship of the wind speed to electricity production (Power in the wind increases as the cube of the wind speed. Because of operational constraints, electricity production increases approximately as the square of the average wind speed). As Figure 1 shows, good wind resources are available in most regions of the country, with only the Southeast and East Central regions without significant resources [7]. A broad area in the U.S., including the region known as the "Great Plains" contains a large amount of wind in the lower-to-moderate power-class ranges (classes 4 and 5, corresponding to 5.6-6.4 m/s average annual wind speeds at 10 meter height). This area reaches from Montana east to western Minnesota and south to Texas. In any region, however, specific locations can benefit from local terrain features that enhance air flow by channeling it through smaller areas, thus increasing its velocity and resulting power density.

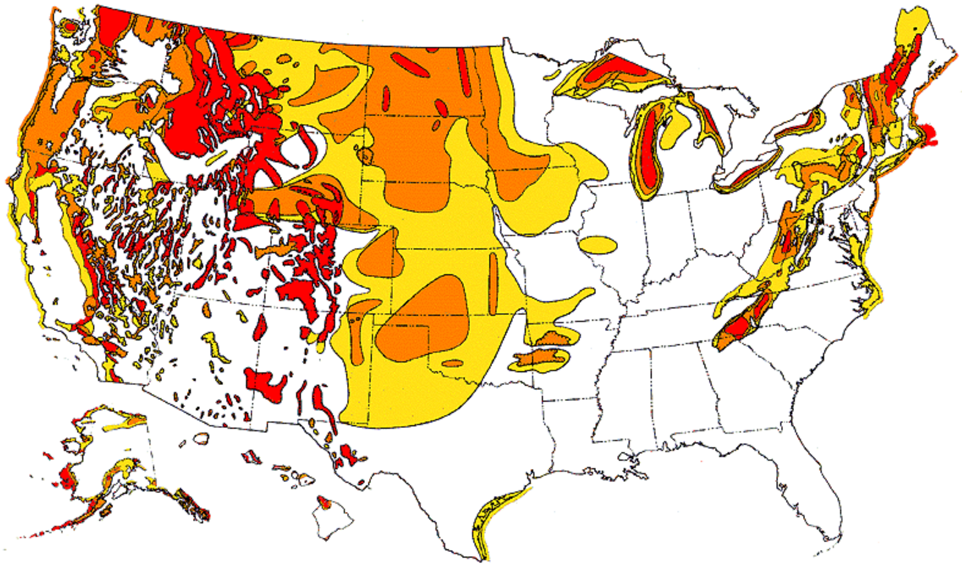
Table 1. Comparison of wind resource classes.

	Avg. Wind Speed Range (m/s @ 10 m)	Wind Power Density Range (W/m^2 at 10 m)	Avg. Wind Speed Range (m/s at 30 m)	Wind Power Density Range (W/m^2 at 30 m)	Electricity Production (Gwh/yr)*
Class 4	5.6-6.0	200-250	6.5-7.0	320-400	1.14
Class 5	6.0-6.4	250-300	7.0-7.4	400-480	1.37
Class 6	6.4-7.0	300-400	7.4-8.2	480-640	1.56

* Based on 1997 technology, 98% availability, 17.5% losses for class 4, 12.5% losses for class 5 and 6, and calculated at the median wind speed. Section 4 discusses loss assumptions in detail.

The wind resource generally becomes stronger as one moves higher above the ground. Thus, the same resource class has a higher potential for producing energy at 30 meters above ground (typical of today's turbines) than at 10 meters. This effect is called vertical shear. The influence of wind shear is illustrated in Table 1 by comparing the wind power density at 10 m and 30 m. While the higher power classes potentially produce more electricity, a turbine must be designed to withstand the higher turbulence and gusts. Turbine designers tailor turbines for conditions such as a specific wind resource class, hub height, turbulence level, and maximum gust level. A successful turbine design for a high wind power class also must be rugged enough to withstand the environment. For example, in California, the Altamont Pass wind regime is relatively benign, while areas of the Tehachapi Pass are known to experience 45 m/s winds during storms which can damage even a parked turbine if it is not designed for these extreme wind conditions. Obviously, design requirements and tradeoffs affect both the lifetime of a turbine and its costs.

Another key tradeoff for the windfarm developer or operator is transmission access, cost and availability. Developers in the Altamont Pass and San Gorgonio Pass are fortunate that large substations are located nearby. They have ready access to the high voltage transmission system which has capacity for power export. On the other hand, the expense of installing dedicated lines to a single windfarm can be very high and can substantially increase the effective installed cost of the plants -- by up to 50%.



Wind Power Class	Wind Energy Resource Potential	Wind Power Density at 30 m [W/m²]	Wind Speed at 10 m [mph]	Wind Speed at 30 m [mph]
3	Moderate	240-320	11.5-12.5	13.4-14.6
4	Good	320-400	12.5-13.4	14.6-15.7
5-7	Excellent	400+	13.4+	15.7+

Figure 1. U.S. wind energy resources.

The cost of transmission access is often not included in levelized cost of energy (COE) estimates from wind and other renewable sources. This factor is often excluded from analyses because such costs are site-specific and hard to estimate. In any specific region or for any particular project, a tradeoff between better wind resources and transmission cost and access will often exist. While the better wind resources produce more energy, they may be more remote and have higher associated site development and transmission costs. Therefore, wind resources in any area are unlikely to be developed cost-effectively exclusively from best sites to marginal sites. Rather, good resources with good transmission access and/or other favorable market factors may be developed before better resource sites with more expensive access or less favorable market factors.

Analysis by PNL has indicated that the amount of land exhibiting power class 4 or higher (land with no restrictions on wind energy development such as urban areas, park land, and bodies of water) is more than 9 percent of the contiguous U.S., or about 700,000 square kilometers [6]. This area is reduced to more than 450,000 km^2 under a PNL-defined "moderate" scenario of land exclusions. The moderate resource scenario excludes environmentally protected lands, urban areas, wetlands, 50% of forest lands, 30% of agricultural lands, and 10% of range and barren lands. The total amount of available land with power class 5 or higher is just over 1% of total land area, or about 90,000 km^2. Using assumptions from the Technology Characterization and the PNL-defined moderate scenario of land exclusions, the resulting land areas equate to approximately 3,500 GW of installed (rated) wind capacity. This is far more than any market penetration estimates. Therefore, market penetration should not be constrained nationally by resource availability. These assumptions for resource use equate to nearly 8 MW of installed (rated) capacity per square kilometer.

Since the amount of electricity generated by wind turbines increases quickly as the resource improves, it makes sense that -- for cases where all other costs are equal -- windfarm projects will tend to use the best resource sites in any region first. Using data from a recent NREL study on the proximity of wind resources to existing transmission capacity [8], Figure 2 shows the amount of available land, assuming the PNL "moderate" scenario, with wind resource classes 4, 5, and 6 within 10 miles (16.1 km) of available transmission lines. This analysis indicates that approximately 14% of current U.S. electric generation could be met by wind energy installed in class 5 or above resources within 10 miles of available transmission lines. Capacity additions beyond that level would have to utilize class 4 resources. The majority of the country's usable wind resource is in class 4. There is more than 25 times the resource available in class 4 than in class 6. For wind to maximize its geographic applicability, class 4 sites will eventually have to become cost effective. Additionally, it is important to remember that resource classes represent continuous ranges of resource quality. Thus, as the better developable sites are depleted, even within a given class, it will be important to keep improving the technology so that the lower wind speed sites will continue to become competitive.

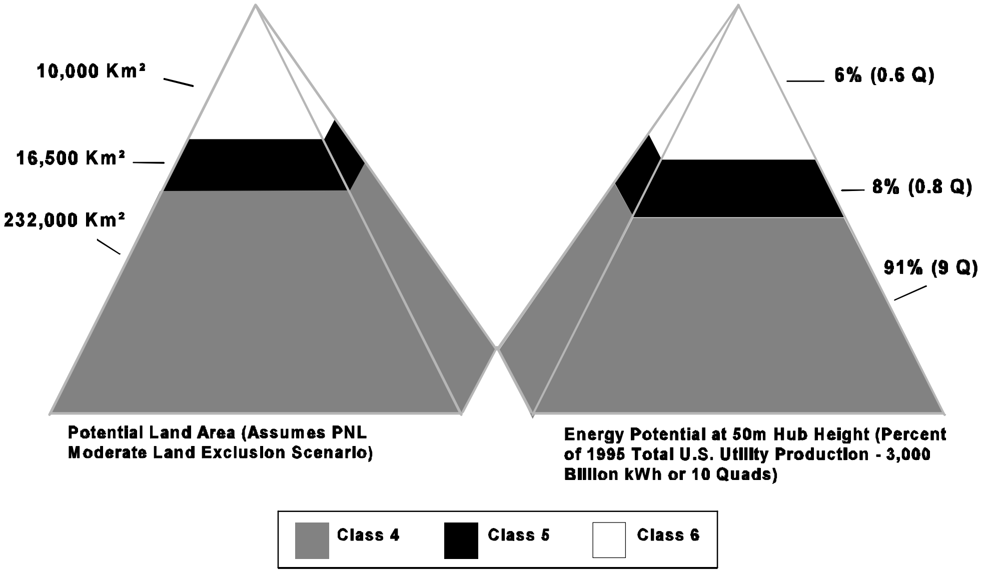


Figure 2. Potential wind energy within ten miles of transmission facilities.

Tools For Conducting Analyses Using Data In This Document

Models are available to calculate cost of energy (COE) or rate of return for various project ownership and financing assumptions [9,10]. The FATE-2P model, developed by Princeton Economic Research, Inc. [10] is used to calculate COEs in a separate chapter of this TC compendium. Commercial tools to assist utilities in customizing analyses of windpower projects for site-specific conditions and turbine-specific design features do not currently exist. A recently developed wind energy curriculum entitled "Harvesting The Wind" is available from the Sustainable Resources Council, Minneapolis, Minnesota [11]. It includes a project feasibility assessment spreadsheet tool suitable for evaluating privately-owned wind energy projects in the Midwest. This tool, available on diskette, allows use of default settings or customized input data for wind resource and turbine characteristics, and financial assumptions. In addition, EPRI recently published a primer for utilities on planning windpower projects [12].