

## Wind Energy Resources

Any plan to develop wind energy must begin by understanding the wind resource. Where are the best potential wind sites located? How much energy could be extracted from the wind at those sites? Will wind turbine performance be affected by turbulence or other wind resource characteristics? These are just a few of the questions that must be answered. This briefing paper describes the U.S. wind energy potential, discusses some basic characteristics of wind resources, and summarizes the key elements of a wind resource assessment program

### Wind energy potential of the United States

The United States is fortunate to possess one of the largest wind energy resources in the world. The amount of energy theoretically available for use has been estimated at as much as 40 times the current U.S. energy consumption. Of course, only a small fraction of this potential could be used because of constraints on available land for wind power plants, limits on the efficiency of energy extraction, cost, siting issues and other factors. Even after taking these factors into account, various studies suggest nonetheless that wind has the potential to supply anywhere from 10 percent to 40 percent of U.S. electricity needs.

#### Wind Classes

To simplify the characterization of wind potential, it is common to assign areas to one of seven wind classes, each representing a range of wind power densities or wind speeds at a specified height above the ground. The standard wind class definitions are shown in Table 1. (The meaning of wind power density is discussed below.)

By and large, the areas being developed today using large wind turbines are ranked as class 5 and above. Class 3 and 4 areas may be developed in the near future as wind turbines are

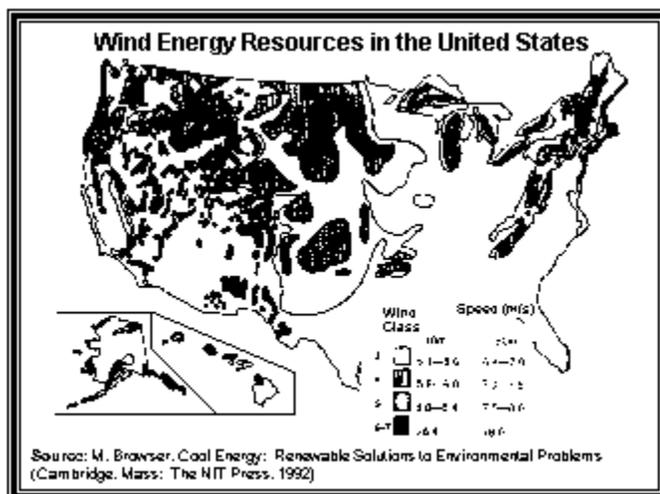
Table 1. Standard Wind Class Definitions

Class	30 m Height		50 m Height	
	Speed (m/s)	Power (W/m <sup>2</sup> )	Speed (m/s)	Power (W/m <sup>2</sup> )
1	0-5.1	0-160	0-5.6	0-200
2	5.1-5.9	160-240	5.6-6.4	200-300
3	5.9-6.5	240-320	6.4-7.0	300-400
4	6.5-7.0	320-400	7.0-7.5	400-500
5	7.0-7.4	400-480	7.5-8.0	500-600
6	7.4-8.2	480-640	8.0-8.8	600-800
7	8.2-11.0	640-1600	8.8-11.9	800-2000

adapted to run more efficiently at lower wind speeds. Class 1 and 2 areas are not deemed suitable for large wind machines, although smaller wind turbines may be economical in areas (such as remote or off-grid communities) where the value of the energy produced is high.

#### Geographic distribution

Wind energy resources are distributed unevenly across the United States (see map).



Most of the class 4 and higher areas are found near the east and west coasts, along ridges in the Rocky and Appalachian mountain systems, and in a wide belt stretching across the Great Plains. The southeastern United States is characterized by class 1 and 2 winds.

### **Constraints on wind potential**

Wind resource classification is only one of the factors that must be considered in estimating wind energy potential. For one thing, not all windy sites are suitable for wind power development. Some are on steep, rocky or inaccessible terrain; others are in scenic or protected forests and parks; still others are in densely populated areas.

One U.S. Department of Energy study that took these factors into account grouped areas of the country into five categories of land use: environmental (such as national parks), urban, forest, cropland and range land. The researchers then constructed four scenarios that considered varying degrees and types of possible land use exclusions to arrive at a range of estimates of the wind energy potential in each wind class.

They found that the windiest areas (class 5 and above) could support enough wind power capacity to provide 18 percent to 53 percent of the electricity consumed in 1993. The lower figure represents the most severe assumptions of land use exclusion, while the upper figure represents no exclusions at all. Most of the prospective sites in these classes are concentrated in the Great Plains states. In contrast, class 3 and 4 areas are distributed much more widely around the country and, according to the study could supply from 1.7 to 6 times the current U.S. electricity demand.

Other constraints may reduce these figures considerably. Two factors not considered in the study were possible conflicts between wind power plants and bird habitats and migration routes and constraints on the transmission capacity needed to carry wind power to population centers. (A recent study by the Energy Information Administration indicates that many windy sites are located near existing transmission lines.) The intermittent nature of wind energy also may impose limitations on its use, although probably not until it begins to generate more than 10 percent of a utility's power needs.

## **Characteristics of wind**

Wind is caused by uneven heating of the earth's surface by the sun. The heat absorbed by the ground or water is transferred to the air, where it causes differences in air temperature, density and pressure. These differences, in turn, create forces that push the air around.

On a global scale, the temperature difference between the tropics and the poles drives the trade winds, which act as a giant heat exchanger to keep the equator from becoming even hotter and the poles from becoming even colder. On a much smaller scale, temperature differences between land and sea and between mountains and valleys often create strong breezes. Wind direction and speed are affected by other factors, as well, such as the earth's rotation, local topographical features and the roughness of terrain.

### **Wind power density**

Like water flowing in a river, wind contains energy that can be converted to electricity using wind turbines. The amount of electricity that wind turbines produce depends upon the amount of energy in the wind passing through the area swept by the wind turbine blades in a unit of time. This energy flow is referred to as the wind power density.

A key aspect of wind power density is its dependence on wind speed cubed. This means that the power contained in the wind

**Characteristics of wind**

- *Wind power density*
- *Variability of winds*
- *Wind speed dependence on height*
- *Spatial variations*

increases very rapidly with wind speed; if the speed doubles, the power increases by a factor of eight. In practice, the relationship between the power output of a wind turbine and wind speed does not follow a

cubic relationship. Below a certain minimum speed, the turbine does not have enough wind to operate, whereas above a certain speed its output levels off or begins to decline. In very high winds the turbine may even be shut down to prevent damage to it.

Wind power density also depends on air density. At higher altitudes, air density decreases and, as a result, so does the available power. This effect can reduce the power output of wind turbines on high mountains by as much as 40 percent compared to the power that could be produced at the same wind speeds at sea level. Air density depends inversely on temperature: colder temperatures are favorable for higher air densities and greater wind power production.

### **Variability of winds**

To accurately predict the performance of wind turbines, one needs to know not only the average wind speed at a particular location but also how wind speed varies over time. It is useful to distinguish between variations on three time scales: short (seconds to minutes), medium (hours to days) and long (weeks to years).

Variations in the short time scale usually are not very important for evaluating the wind resource unless the wind is very turbulent or frequently changes direction. For single wind turbines, abrupt wind speed changes can cause large fluctuations in power output. In wind power plants that contain many wind turbines, however, this effect tends to average out because wind machines at different locations experience gusts at different times. For this reason, wind speed measurements intended to evaluate a potential wind power site normally are averaged over a period of 10 minutes to one hour. However, unusually gusty or turbulent winds can cause extra wear on wind turbine components and increase repair and maintenance costs.

Variations occurring over hours to days are very important for wind resource evaluation. Wind speed records typically show large upswings and downswings that persist for up to several days, reflecting passing storms and weather fronts. In addition, many locations experience a daily pattern of wind speed variation, with peak winds often occurring in the afternoon.

Monthly and seasonal variations also have a significant effect on wind power plant performance. The degree and timing of seasonal variations depend upon the region. In most parts of the United States, winds are stronger in winter and spring because of more frequent storms and greater high-altitude wind speeds. However, mountain passes near the coasts (like Altamont Pass near San Francisco) may see their strongest winds in summer because differential temperatures and pressures between the warm land and cool ocean are greatest then. There may even be changes in the annual average wind speed from year to year related to regional climate phenomena.

How long should wind speeds be recorded to estimate the long-term performance of wind power plants? At least one year of measurement is essential to capture seasonal wind behavior. Beyond that, the benefits of extended measurement diminish quickly, and one to two years of measurement usually will suffice to predict long-term average wind speeds and wind speed variability with acceptable accuracy. It is sometimes possible to improve the accuracy of predictions by comparing the on-site measurements with the long-term wind speed record from a nearby weather station.

### **Wind speed dependence on height**

Wind speed tends to increase with height in most locations, a phenomenon known as wind shear. The degree of wind shear depends mainly upon two factors, atmospheric mixing and the roughness of the terrain.

Atmospheric mixing typically follows a daily cycle driven by solar heating. At the hub height of a wind turbine, this cycle often causes wind speeds to increase in the daytime and decrease at night. However, the range of variation between night and day typically diminishes as hub height increases. At a height of approximately 10 meters, the diurnal variation can be very pronounced; as the height increases to approximately 50 meters, it weakens or may even disappear.

Terrain roughness also affects wind shear by determining how much the wind is slowed near the ground. In areas with a high degree of roughness, such as forests or cities, near-surface wind speeds tend to be low and wind shear high, whereas the converse is true in areas of low roughness such as flat, open fields. Wind shear may be greatly reduced or eliminated where there is an abrupt change in terrain height such as a sea cliff or mountain ridge.

To save money, wind measurements sometimes are taken at a lower height than the wind turbine tower. In that case, it is essential to measure wind shear at different times of day and in different seasons to accurately predict the performance of a wind power plant. The shear can be measured by monitoring wind speeds at two or three heights on a tower. Since wind turbines produce much more power in stronger winds, wind turbine designers try to put turbines on the tallest possible towers. At some point, however, the increased cost of towers outweighs the benefits. With current wind turbine technology, the optimum tower height for large wind machines appears to be approximately 40 to 50 meters.

### **Spatial variations**

To further complicate matters, wind resource characteristics can differ greatly between nearby locations. For obvious reasons, the strongest winds usually are found in well-exposed locations. In addition, terrain features such as hills and ridges can accelerate the wind as it passes over them. A ridge oriented perpendicular to the prevailing wind direction and with a moderate slope is usually ideal. However, strong winds may sometimes occur in unexpected places. For example, broad mountain passes may be ideal for wind power plants because they channel winds passing over a mountain range and because breezes may be created by cold air sinking from mountain tops into valleys. Meteorologists have developed a variety of tools for predicting wind speeds in complex terrain, including sophisticated computer models. There is no substitute, however, for direct measurement.

*Monthly and season wind variations have a significant effect on wind power plant performance.*

## **Developing a wind resource assessment program**

One of the first steps for states and utility companies to consider when developing wind as an energy source is to survey the available wind resource. Unfortunately, reliable wind speed records suitable for wind resource assessment can be difficult to obtain, and many that have been collected are not available to the general public. Nevertheless, there is usually enough data to make a preliminary judgment about the feasibility of wind energy development. One of the best sources of information is the *Wind Energy Resource Atlas* of the United States. This book (published by the National Renewable Energy Laboratory) provides maps of estimated wind energy classes for each state, as well as information about climate, topography and wind resource measurement.

If wind development seems feasible for a state or region, the next step could be to conduct a resource assessment program. The federal government, through the National Renewable Energy Laboratory, provides technical support and some funding for such programs. One example is the Utility Wind Resource Assessment Program (U\*WRAP); its goal is to increase the quality and quantity of wind data available to electric utilities. In general, a wind resource assessment program can include any or all of the following elements.

### Components of a wind resource assessment program

- Large area screening
- Site visits
- Wind speed monitoring
- Micrositing

### Large area screening

In this stage, the entire region is surveyed to make a preliminary assessment of areas that may be suitable for wind energy development. This step may be appropriate if the region is large (say, the size of a state), if no previous wind measurement program has been conducted there, or if previous programs were incomplete or not systematically designed and implemented. A large-area screening usually begins with a review of existing wind resource maps and other

meteorological information, analysis of the meteorological characteristics of the state and their possible effect on wind speeds, and development of screening criteria (such as terrain form, current use, vegetation cover and accessibility to roads and transmission). One recent approach to large-area screening uses geographical information systems (GIS), a computer mapping and analysis tool, to screen potential sites.

### Site visits

Once a preliminary list of sites is developed, the next step is usually to send field teams to visit the sites. One purpose of such visits is to look for physical evidence to support the wind resource estimate developed in the large-area screening. Consistently bent trees and vegetation, for example, are a sure sign of strong winds. Another purpose is to check for potential siting constraints. A site may prove inaccessible, there may be competing land uses, it may be difficult to gain permitting approval for the wind plant or its transmission lines, or local land owners may express strong resistance to selling the necessary land and easements. A third purpose of the site visit is to select a possible location for a wind monitoring station.

### Wind speed monitoring

Once a set of promising sites has been identified through large-area screening and site visits, equipment can be installed to monitor wind speeds for up to two or three years. The site chosen for the equipment should be as representative as possible of the locations that might actually be developed for wind power. Two or three measuring devices (anemometers) should be placed on each tower to measure wind shear. Often, the anemometers transmit data over a cellular phone connection to a central computer, where the data can be stored and analyzed. Extreme care must be taken throughout the process to ensure accurate measurements and to keep to a minimum any data loss caused by equipment failures. The number of sites chosen for monitoring depends upon the situation; a typical number of sites for a state might be 10 to 30. Out of this number, two or three sites might realistically be chosen for subsequent wind development. The cost of installing and operating a single site for two years ranges from \$25,000 to \$40,000. With multiple sites, the cost per site decreases to perhaps \$19,000 to \$30,000.

### Micrositing

The most advanced stage of a wind resource assessment program is micrositing. This process involves conducting surveys and monitoring at individual sites to quantify the small-scale variations in the wind resource over the area. In complex terrain, micrositing may involve numerous wind speed measurements combined with computer modeling to predict speeds in areas where no measurements are taken. Once completed, the results of the micrositing survey are used to position the wind turbines in a wind power plant to maximize their energy output.

## For more information

American Wind Energy Association, *Recommended Practice for the Siting of Wind Energy Conversion Systems*, AWEA Standard 8.2 (Washington, D.C.: AWEA, 1993).

AWS Scientific, *U\*WRAP Handbook* (Albany, N.Y.: AWS, 1996).

D.L. Elliott, L.L. Wendell, and G.L. Gower, *An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States* (Golden, Colo.: National Renewable Energy Laboratory, 1991).

T. Hiester and W. Pennell, *The Meteorological Aspects of Siting Large Wind Turbines*, Report No. PNL-2522 (Springfield, Va.: National Technical Information Service, 1981)

Pacific Northwest Laboratory, *Wind Resource Atlas of the United States* (Golden, Colo.: National Renewable Energy Laboratory, 1987).

David A. Spera (ed.), *Wind Turbine Technology*, Chapter 8 (New York: American Society of Mechanical Engineers Press, 1994).

*A first step in developing wind as an energy source is to survey the available wind resource.*

### **National Wind Coordinating Committee**

The content and form of the papers in this series have been reviewed and approved by the National Wind Coordinating Committee. Committee members include representatives from investor-owned utilities, public utilities, state legislatures, state utility commissions, state land commissions, consumer advocacy offices, state energy offices and environmental organizations. The purpose of the National Wind Coordinating Committee is to ensure the responsible use of wind power in the United States. The committee identifies issues that affect the use of wind power, established dialogue among key stakeholders and catalyzes appropriate activities.

---

*The Wind Energy Series is a product of the National Wind Coordinating Committee (NWCC). The NWCC is a collaborative endeavor that includes representatives from electric utilities and support organizations, state legislatures, state utility commissions, consumer advocacy offices, wind equipment suppliers and developers, green power marketers, environmental organizations, and state and federal agencies.*

[Issue Brief No. 4](#) | [NWCC Publications](#)