Future Energy: Opportunities and Challenges

Part II. Energy Sources

Chapter 8. Wind Energy

Future Energy:
Opportunities and Challenges

Thomas W. Kerlin

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Wind Energy

The Main Points

- **Uneven solar heating of the earth is the main initiator of atmospheric wind flows.**
- **Wind speed increases with elevation above the surface.**
- **Estimated U.S. wind energy potential is greater than current U.S. electricity production.**
- **The intermittency of wind energy imposes extra requirements on the electrical grid.**
- **Wind turbines with electrical power ratings of as great as 7 megawatts are available, and even larger machines are in design.**
- **Producing a Quad of electricity per year would require around 45,000 wind turbines if each had a maximum rating of 2.5 megawatts.**

8.1 Introduction

Wind is air in motion, and, consequently, it possesses kinetic energy. The purpose of a wind turbine is to transfer as much of that energy as possible to a rotating shaft that can then do mechanical work. The mechanical energy is most often used to drive an electric generator.

Uneven heating of the earth by the sun is the main initiator of atmospheric wind flows. Solar heating varies with cloud cover, the condition of the surface (water, ice, forest, desert, etc.), and the distance from the equator. Heated air rises in the warmer regions and is replaced by air flowing from cooler regions. In addition, surface features, gravity, and the earth's rotation influence wind direction and strength.

The total energy contained in the earth's winds is enormous (estimated to be about 2 percent of the solar energy that reaches the earth[1,2]). This wind energy eventually degrades to heat through friction with objects and the atmosphere. Even though wind energy is diffuse and variable, it is an important and growing part of the world's energy supply.

8.2 Wind Energy Potential

A system for classifying wind energy potential is based on the specification of seven categories, as shown in Table 8-1.[3]

Table 8-1. Wind Energy Categories

Class	Wind Speed (mph) at 33 ft Elevation	Wind Speed (mph) at 164 ft Elevation
1	9.8	12.5
2	11.5	14.3
3	12.5	15.7
4	13.4	16.8
5	14.3	17.9
6	15.7	19.7
7	21.1	26.6

Winds of Class 3 and above are needed for practical wind energy applications.

The best approach for estimating the potential for wind energy is a detailed region-by-region analysis of average wind speeds, wind speed variability, and site suitability. The Pacific Northwest Laboratory (PNL), now renamed the Pacific Northwest National Laboratory (PNNL), has performed such an analysis[3]. The PNL report considered the capability of current and advanced wind machine technology, the availability of suitable winds, and the availability of land needed for wind machines (with possible shared use for farming or grazing).

With technology that can exploit winds of Class 3 and above, the estimated total U.S. wind energy potential is 16 to 57 electrical Quads per year. The range of values is due to differences in assumed exclusions of suitable lands because of demands for other use. Recall that annual electrical energy consumption in the U.S. is about 14 Quads (2010).

8.3 Wind Energy Physics

It can be shown (see Appendix P) that the power in moving air is given by

$$\text{Power} = (1/2)\rho A v^3 \qquad \text{(8-1)}$$

where

ρ	=	density of air
A	=	cross-sectional area of the air stream (the same as the area facing the air flow to the turbine)
v	=	speed of the wind

This expression shows the power in the air stream is proportional to the area swept by the blades of the wind turbine facing the air flow and proportional to the cube of the wind speed. It is important to note the cubic relationship between wind speed and power. For example, a doubling of the wind speed increases the power by a factor of eight (two cubed or 2×2×2).

Practical devices for capturing wind power are capable of capturing only a fraction of the total power in the air stream. It has been shown that the maximum efficiency of power capture is 59 percent (the Lanchester-Betz-Joukowsky Limit[4], named after its discoverers), but actual machines are somewhat less efficient.

The capital expense of wind machines is justifiable in locations where the wind is adequately consistent and strong. As mentioned, an average wind speed of 12.5 miles per hour (Class 3 wind) is considered essential.

Wind speed increases with height above the ground[5]. The speed increases approximately as the 1/7 power of the height or

$$v_h = (v_o)(h/h_o)^{1/7} \qquad (8\text{-}2)$$

where

v_h = wind speed at a height h above the ground
v_o = wind speed at a reference height h_o above the ground

Table 8-2 shows predicted wind speeds and power relative to the wind speed and power at 10 feet above the ground.

Table 8-2. Wind Speeds Relative to Wind Speed at 10 Feet Above the Ground

Height (ft)	Wind Speed/Wind Speed at 10 ft	Wind Power/Wind Power at 10 ft
10	1	1
20	1.10	1.35
50	1.26	1.99
100	1.39	2.69
200	1.53	3.62
500	1.74	5.36
1,000	1.92	7.21

Clearly, for maximizing power capture, it is advantageous to position wind machines as high as possible above the ground.

8.4 Wind Energy Machines

There are two main types of wind energy machines: horizontal-axis and vertical-axis.

Horizontal-axis machines have blades (usually three in number) mounted on a horizontal shaft. The shaft rotates in a housing that rests on a swivel base atop a tall tower. In operation, the blades are oriented so as to face the wind. An electric generator in the housing converts shaft rotation into electricity. Typical horizontal-axis machines are shown in Figures 8-1 and 8-2.

Figure 8-1. A Horizontal-Axis Wind Turbine (courtesy of U.S. Dept. of Energy)

A typical large horizontal-axis wind machine has a rated power output of 2.5 megawatts electric (MWe). The size of these machines is impressive. They are mounted on towers that are about 275 feet tall, have blades that are about 145 feet long, and contain about 500 tons of steel. The trend is to ever larger machines (7 megawatt machines are available, and even larger machines are under development). The housing at the top of the tower for the power conversion equipment, called the nacelle, is large enough for a person to walk around inside while performing maintenance activities. Manufacturing wind machines is a huge, time-consuming activity. However, the prefabrication of components permits rapid installation.

Vertical-axis machines have blades mounted on a vertical tower. There are two main types of vertical-axis wind turbines: the Savonius type and the Darrieus type. Both are named after their inventor. The Darrieus machines

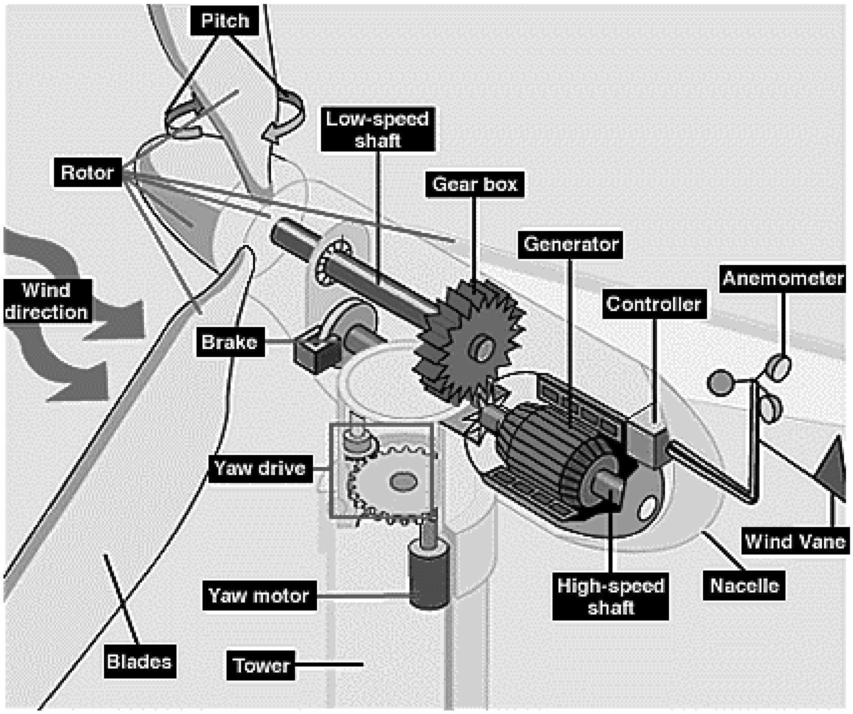

Figure 8-2. Horizontal Wind Turbine Internals (courtesy of U.S. Dept. of Energy)

use airfoils connected to a vertical shaft. A simple configuration appears in Figure 8-3. The Savonious machines have opposite-facing troughs on opposite sides of the vertical shaft around which they rotate (see Figure 8-4). Wind forces transfer more energy to the concave side than to the convex side, causing the rotor to spin around the axis. Variations on the Savonious and Darrieus designs have been conceived and are under development for possible commercial applications. It is generally thought Savonious machines are suitable only for small-scale applications, while Darrieus machines may be suitable for use in central station power plants, usually called wind farms.

Vertical-axis machines have their generators located on the ground, an advantage relative to horizontal-axis machines. However, the features of vertical-axis machines dictate a location close to the ground, where wind velocity is lowest, which is a disadvantage relative to horizontal-axis machines.

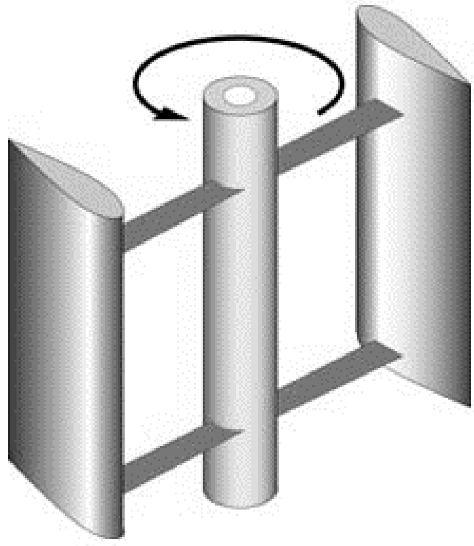

Figure 8-3. A Darrieus Wind Turbine (Giancarlo Rossi, Wikimedia, CC BY-SA 3.0)

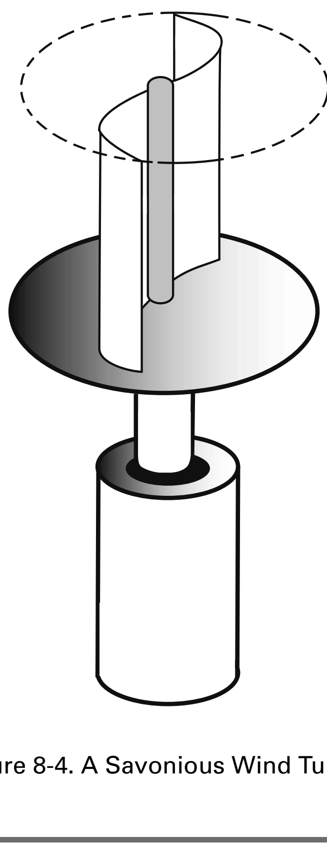

Figure 8-4. A Savonious Wind Turbine

Horizontal axis machines and vertical axis machines have some strong advocates, but horizontal-axis machines have captured all of the commercial market for large-scale production to date.

Wind machines in very cold climates require protection against ice build-up on the blades. Machines with heaters in the blades are available.

There is some interest in wind machines mounted on helium balloons. Proponents believe the higher speed and more persistent winds at higher altitudes are a benefit that could offset the greater complexity and cost of a balloon-mounted wind machine.

8.5 Intermittency

The variability of wind power imposes constraints on reliance on this energy source. Either excess energy from wind machines must be stored for use during windless periods and periods of low wind speed, or wind machines must be part of a system that includes other types of power producers that can compensate for temporary changes in wind power.

Possible energy storage strategies include hydrogen production by electrolysis, pumped water storage, and battery charging.

Fossil, nuclear, hydroelectric, and/or geothermal plants may to be used to compensate for power needs caused by wind power changes due to wind intermittency. Since power supplied to the grid must instantaneously match electricity demands, any changes in power generation from one source must quickly be matched by compensating changes in power generation from one or more other sources. This matching of power generation to demand, called load following, is always required, but the requirement for ability to change power generation quickly in load following plants increases with the large and frequent power output changes from wind power. Not only does this type of load following cause increased wear and tear on generation equipment, it also causes affected plants to operate in a manner that may not be economically optimum, and it imposes additional demands on the grid and increases the standby generation capacity that must be available when wind power generation decreases.

Most of the power plants assigned load following duty are fueled with natural gas. These plants are well-suited for load following because their capital cost is small compared to their operating cost, and they can come on stream quickly as needed. Hydroelectric plants are also well-suited for load following because they respond rapidly, and the water is available for use at any time without a performance penalty. Consequently, they share in load following duty even though their capital cost is much greater than their operating cost. Since nuclear plants have lower fuel cost and higher capital costs than fossil fuel plants, it is desirable to operate them at full power continuously.

8.6 Wind Machine Siting

Wind machines may be located on land or in the sea. Site suitability for either location depends on local average wind speeds and wind speed variability. Favorable U.S. sites are concentrated in the Midwest and along some coastlines. The top five states in terms of wind energy potential are North Dakota, South Dakota, Montana, Wyoming, and Minnesota. These states have suitable wind conditions and an abundance of open, sparsely populated land, much of which is used for farming or grazing. Wind machines can coexist with these activities, providing landowners with a new source of income. However, these areas lack the extensive electrical grid that is needed to transport electricity to areas with high demand. Building new transmission facilities would be required to bring the energy from these areas to where it is needed.

Some offshore locations offer suitably strong and consistent winds. This, along with a possible absence of competition for other uses of the site and (most often) proximity to electrical load centers near the coasts, makes offshore siting attractive. The disadvantages are the added cost and complexity of building and maintaining offshore rigs, the need for underwater transmission lines, vulnerability to strong storms, possible interference with fishing, and the possible impact on shoreline scenery (a major source of opposition by shoreline residents, but not a problem for sites far enough away from the shore). Offshore systems may be built in shallow water on platforms that rest on the sea floor or in deep water on floating structures. Most offshore systems currently in operation are in shallow water, but the stronger and less-variable winds farther from shore and the elimination of structures that are visible from shore are motivating interest in deep-water systems.

8.7 Wind Energy Status and Prospects

In 2007, total world-installed wind energy capacity reached about 10,000 MWe, and U.S. capacity reached about 1500 MWe. The growth rate is at least 25 to 30 percent per year. Newer wind machine installations use large machines (2.5 MWe and larger) located in wind farms with multiple machines (for example, the Roscoe Wind Farm in Texas has 627 wind turbines with a combined capacity of 781.5 MWe.) For total world wind machine capacity of 10,000 MWe, and for operating at 30 percent availability, electricity production is 26.3 billion kilowatt hours per year or 0.09 Quads of electrical energy per year.

The U.S. wind energy production capacity in 2007 was around 0.013 Quads (about 0.1 percent of total U.S. electricity consumption). Clearly, wind energy production is growing rapidly, but it now provides only a small fraction of electricity production. If the growth of wind energy capacity continues at 30 percent per year, it will take around 15 years (from 2007) to reach a capacity of one Quad of electrical energy per year.

A single 2.5 MWe wind machine operating at 30 percent availability produces 6,570,000 kilowatt hours per year. Production of one Quad of electrical energy per year would require 45,000 such machines. Production of 45,000 machines would be a huge undertaking, requiring about 2 ¼ million tons of steel (about 2 ¼ percent of annual U.S. steel production).

Wind energy is destined to be a major energy source for the U.S. and the world in the future. Wind turbines can provide cost-competitive electricity with little environmental impact. The biggest hurdles are constructing enough machines to permit significant production, overcoming siting objections, dealing with intermittency (especially its impact on the electrical grid), and building transmission lines to carry the electricity from wind farms to users.

References

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2. *McGraw-Hill Encyclopedia of Science and Technology, 9th edition,* Vol. 19, p. 559 New York: McGraw-Hill, 2002.

3. Elliott, D. L., Wendell, L. L. and Gower, G. L. "An Assessment of the Available Wind Land Area and Wind Energy Potential in the Contiguous U.S." *Pacific Northwest Laboratory Report PNL-7789* August 1991.

4. Van Kuik, G. "The Lanchester-Betz-Joukowsky-Limit" *Wind Energy*, Vol. 10, 2007, pp. 289–291.

5. Wind Power Calculator at http://windpower.generatorguide.net/wind-speed-power.html.

Exercises

8-1. What is the maximum power available from a horizontal axis wind turbine with blades 100 feet long in a wind blowing at 18 miles per hour?

8-2. A farmer wants to use a wind turbine to pump water into an elevated tank located 25 feet above the ground, to be used to water his livestock. The average wind speed at an elevation of 50 feet is 14 miles per hour. He plans to place the turbine on a 50 foot tower. How much water could he pump into the tank on an average day with a horizontal axis machine with blades 20 feet long? Assume the pump efficiency is 90 percent.

8-3. It is undesirable to have a large fraction of electricity production in a system from wind turbines. Why is this so?

8-4. A horizontal axis wind turbine has blades with a length of 145 feet. It produces 2.5 MWe for a certain wind velocity. How long should the blades be for a turbine that produces 5 MWe in the same wind?