ENCYCLOPEDIA ARTICLE

Wind power

The extraction of kinetic energy from the wind and conversion of it into a useful type of energy: thermal, mechanical, or electrical. Wind power has been used for centuries.

A small dc horizontal-axis wind machine for rural use.

Early development

Windmills were used extensively in the Middle East by the eleventh century and in Europe by the thirteenth century. By the fourteenth century the Dutch used them for draining marshes and lakes. By the end of the nineteenth century, in Denmark there were about 2500 electricity-producing windmills with a generating capacity of about 30 MW, and about 4600 windmills being used for agricultural applications. Farmers and ranchers in the western United States began using small water-pumping windmills in the midnineteenth century. These wind machines were simple durable multibladed turbines with a high starting torque. An estimated 6.5 million machines were sold between 1880 and 1930, and in the 1930s the annual energy output was equivalent to 10^9 kWh per year. Beginning about 1925, small 0.2–3 kW horizontal-axis machines supplying dc electricity to operate appliances, usually at 32 V, were used in rural areas of the United States (**Fig. 1**). The creation of the Rural Electrification Administration in 1936 soon brought electrical service to these rural areas and doomed the widespread use of the small machines.

In 1941, a 175-ft-diameter (53-m) 1250-kW-capacity wind turbine was added to the generating system of Central Vermont Public Service Corporation. The machine was located on a 2000-ft (600-m) knob near Rutland, Vermont, and operated until 1945, when one of the blade spars broke and a blade was thrown 750 ft (230 m). The machine was scrapped after the accident, and for all practical purposes the development of wind power in the United States was discontinued until the early 1970s.

Energy in the wind

It has been estimated that the total wind power in the atmosphere averages about 3.6×10^{12} kW, which is an annual energy of about 107,000 quads (1 quad = 2.931×10^{11} kWh). Obviously, only a fraction of this wind energy can be extracted, estimated to be a maximum of 4000 quads per year. The power P in the wind per unit area is given by Eq. (1), where V is wind speed

$$P = \frac{\rho V^3}{2} \qquad \mathrm{W/m^2} \tag{1}$$

in m/s and ρ is the air density in kg/m^3, which varies from about 1.225 at sea level to 75% this value at 11,000 ft (3000 m) elevation. According to what is commonly known as the Betz limit, a maximum of 59% of this power can be extracted by a wind machine. Practical machines actually extract from 5 to 45% of the available power. Because the available wind power varies with the cube of wind speed, it is very important to find areas with high average wind speeds to locate wind machines. Examples of good areas in the United States are certain mountain passes and ridges in California and Hawaii, and the flat plains in the midwestern regions of the United States. See also: Wind

Wind-produced electricity

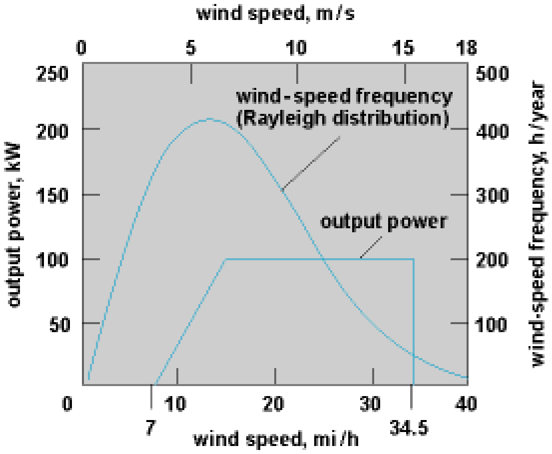
Most research on wind power has been concerned with producing electricity. This effort restarted in the United States in the early 1970s. At present, nearly all the electricity produced in the United States is generated by fossil fuel plants (oil, natural gas, and coal), nuclear plants, and hydroelectric plants. There is concern about fossil fuel generation because the carbon dioxide produced when fossil fuels are burned contributes to the greenhouse effect. Disposal of radioactive waste and concerns about accidents have greatly diminished the expected role of nuclear power, and there is limited hydroelectric power left available for development. The best new sources are conservation and renewable generation. See also: Electric power generation; Energy sources; Nuclear power

The 2500-kW Mod-2 wind machine at Goodnoe Hills near Goldendale, Washington.

Wind power is a renewable energy source that has virtually no environmental problems. However, wind power has limitations. Wind machines are expensive and can be located only where there is adequate wind. These high-wind areas may not be easily accessible or near existing high-voltage lines for transmitting the wind-generated energy. Another disadvantage occurs because the demand for electricity varies with time, and electricity production must follow the demand cycle. Since wind power varies randomly, it may not be available when needed. The storage of electrical energy is difficult and expensive, so that wind power must be used in parallel with some other type of generator or with nonelectrical storage. Wind power teamed with hydroelectric generators is attractive because the water can be used for energy storage, and operation with underground compressed-air storage is another option. See also: Energy storage; Pumped storage;

Waterpower

Approximate Mod-0 power output curve and Rayleigh wind-speed distribution for average wind speed of 16 mi/h (7.2 m/s). The sharp cutoff in output power at a wind speed of 34.5 mi/h (15.4 m/s) is caused by the wind machine shutting down for safety at high speeds.



At present, the best locations for wind power are sites where average wind speeds are high and where nearby conventional generation has a high incremental cost, so that when wind power is available it can produce large cost savings. This combination of factors occurs in California. As a result, by the end of 1985 there were about 13,370 wind generators operating in that state with a total capacity of approximately 1120 MW (a large nuclear plant is about 1100 MW). Most of these machines are grouped into wind farms in mountain passes.

Types of wind machines

The most common type of wind turbine for producing electricity has a horizontal axis, with two or more aerodynamic blades mounted on the horizontal shaft. The wind machine shown in Fig. 1 is a small horizontal-axis turbine. With a horizontal-axis machine, the blade tips can travel at several times the wind speed, which results in a high efficiency. The blade shape is designed by using the same aerodynamic theory as for aircraft. See also: Propeller (aircraft)

Several large wind machines were built by the National Aeronautics and Space Administration under the sponsorship of the Department of Energy. The Mod-0 had a two-bladed 125-ft-diameter (38-m) rotor, which rotated at 40 revolutions/min and drove a 100-kW synchronous generator. The rotor height was 100 ft (30.5 m). The Mod-1 had a two-bladed, 202-ft-diameter (61.5-m), 35-revolutions/min rotor, which drove a 2000-kW synchronous generator. The hub height was 140 ft (42.7 m). The Mod-2 (**Fig. 2**) had a two-bladed, 300-ft (91.4 m), 17.5-revolutions/min rotor driving a 2500-kW synchronous generator. The hub height was 200 ft (61 m). The Mod-0 and a later version named the Mod-0A operated satisfactorily. The Mod-1 and Mod-2 had serious problems.

Many other small horizontal-axis machines are produced. The wind farms in California are mainly composed of these machines, with sizes ranging from a few kilowatts to over 200 kW per machine. Vertical-axis machines have also been investigated. The most common vertical-axis machine is the Darrieus or eggbeater. Two or more curved blades are attached to each end of a vertical shaft. The Darrieus machine has not been as widely used as the horizontal-axis machine for producing electricity.

Estimating energy output

The energy output from a wind machine can be estimated from the graph of machine power output versus wind speed and the wind characteristics at a site. A simplified graph of output power as a function of wind speed measured at a height of 30 ft (9.1 m) for the Mod-0 wind machine is shown in **Fig. 3**.

Often the wind characteristic at a site is simply specified by the average wind speed. However, wind speed V is a random variable about this average value. The Rayleigh distribution, given in Eq. (2),

$$f(V) = \frac{2V}{c^2} e^{-(V/c)^2} \qquad (2)$$

often approximates the wind-speed variation. Here, $f(V)$ is the frequency with which various wind speeds occur, and c is related to the average wind speed V_{av} by Eq. (3). The

$$c = \frac{2V_{\mathrm{av}}}{\sqrt{\pi}} \qquad (3)$$

Rayleigh distribution of wind-speed frequencies for V_{av} = 16 mi/h (7.2 m/s) is shown in Fig. 3. This curve gives the hours per year the wind is in each 1-mi/h range. For example, it can be seen that the wind would be at 20 mi/h about 320 h per year. See also: Probability; Statistics

The yearly wind-machine output can be determined by multiplying the output at each wind speed by the number of hours that the wind is at that speed and then summing for all wind speeds. For the example of Fig. 3, it is calculated that this wind machine would produce 590,000 kWh per year if it was available for operation 100% of the time. This means the wind machine has an average output of 67% of its maximum, which is a very high percentage. However, a wind site with an average wind speed of 16 mi/h (7.2 m/s) at 30 ft (9.1 m) elevation is also an exceptionally good wind site.

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