PDHonline Course E296 (3 PDH)

Wind Energy Systems

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2025

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Wind Energy Systems

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Introduction

The United States faces many challenges as it prepares to meet its energy needs in the twenty-first century. Electricity supply crises, fluctuating natural gas and gasoline prices, heightened concerns about the security of the domestic energy infrastructure and of foreign sources of supply, and uncertainties about the benefits of utility restructuring are all elements of the energy policy challenge. Wind energy is an important part of the diverse energy portfolio that is needed for a stable, reliable energy sector in the United States.

Wind is one of the lowest cost renewable generation sources. Wind turbines range in size from small 5 kW units to large utility scaled units of 2-3 megawatts. Wind turbines for utility applications are usually grouped together into large 50-100 MW wind farms.

Of course, wind generators need wind to produce power and lots of it. A large wind generator will require wind speeds of over 25 mph to reach its nameplate output rating.

Wind is a form of solar energy. Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetation.

The terms *wind energy* and *wind power* describe the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water), or a generator can convert this mechanical power into electricity.

A wind turbine works by using the wind to turn blades, which spin a shaft, which connects to a generator and makes electricity.

By the end of 2025 there was over 153 gigawatts (GW) of wind generation installed in the United States and producing 454,000 gigawatt hours annually. The interest in wind is being driven by global warming, high natural gas prices, and public policy.

The US has about 1,250 GW of electric generation.

The pie chart in Figure 1 on the following page shows the total electric energy production in the United States in 2025 by fuel type. As you can see in the chart, natural gas is the predominant fuel source (40%) while coal is now only 20% (compared to over 50% in 2005) and nuclear power accounts for 20% of the production in the US. Non-hydroelectric renewables make up about 10% of the total energy production in the United States.

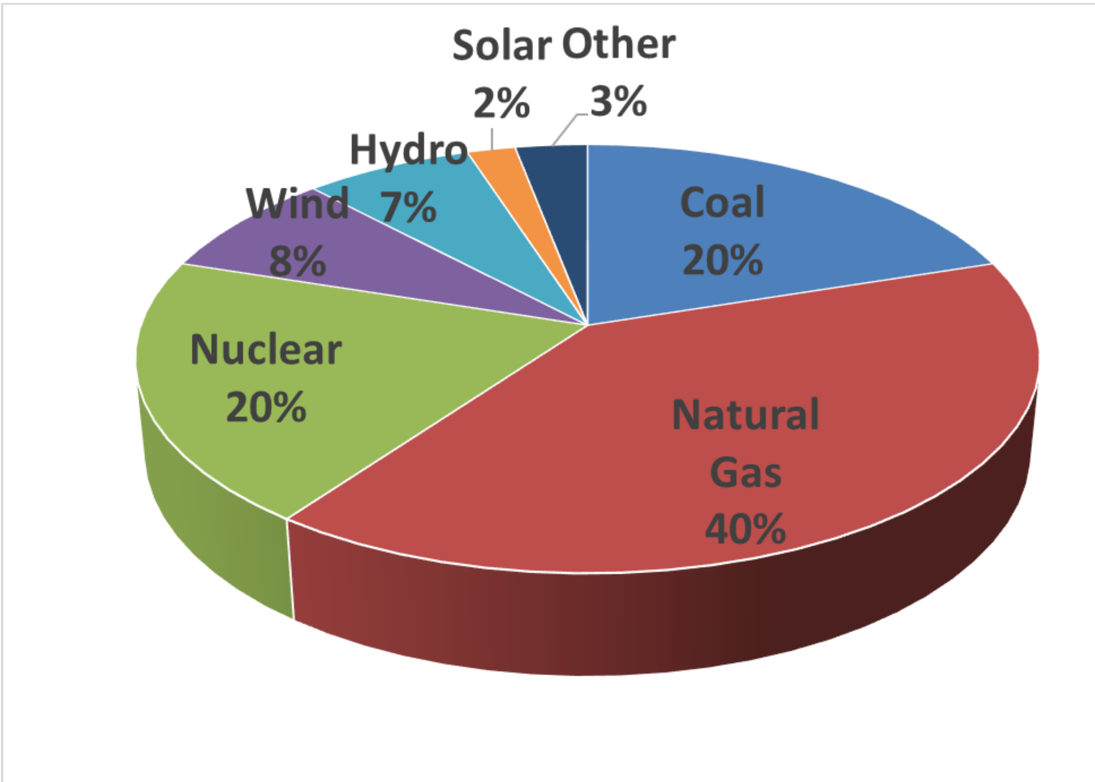


Figure 1

The next chart (Figure 2) shows how the 10% of non-hydro renewable energy production in the United States is distributed. Wind is the largest renewable energy producer and accounts for about 66% of the renewable energy production. Solar is next at 25%. Biomass waste is next at 5% of the renewable energy production, followed by geothermal energy (4%) municipal solid waste (MSW) at 1%.

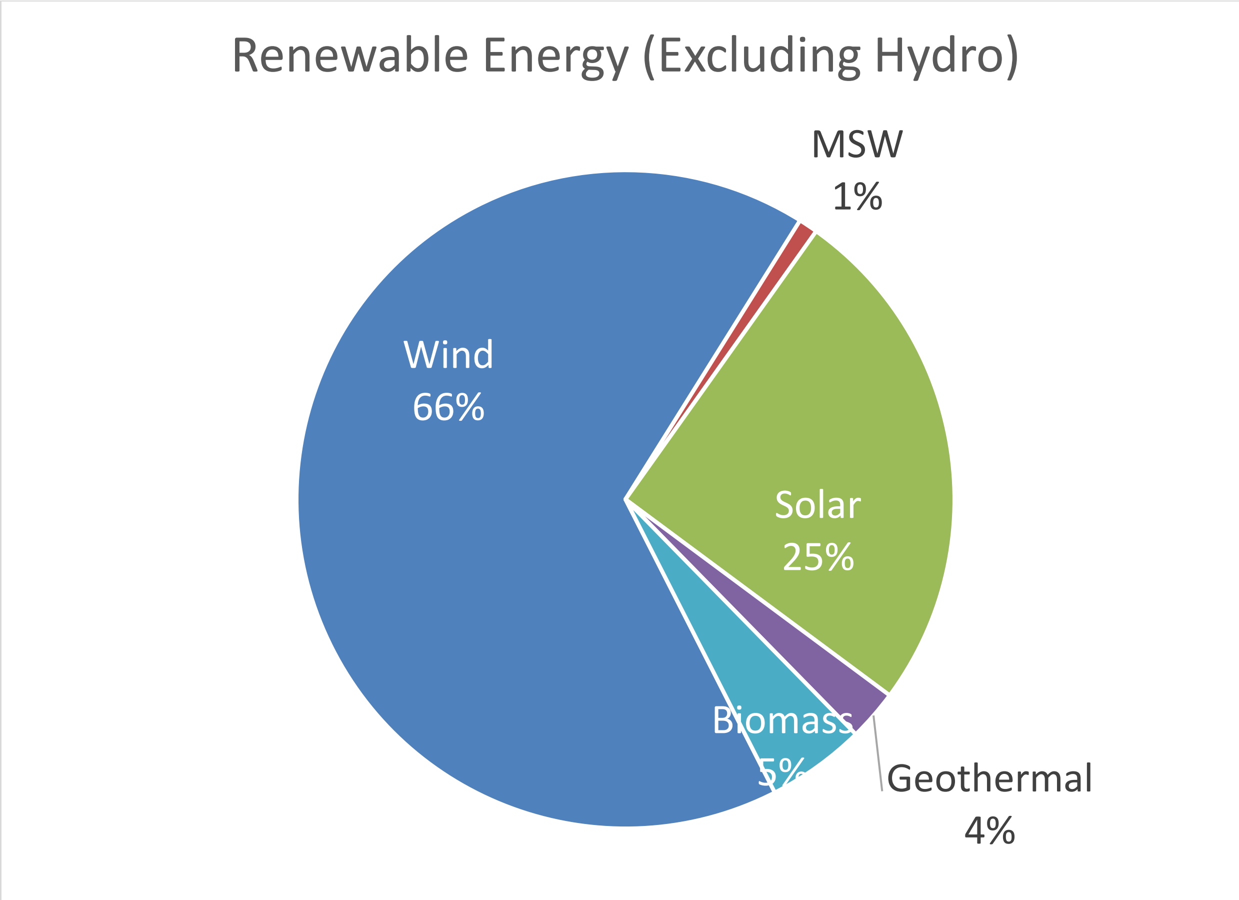


Figure 2

Wind energy is not a new concept. Since ancient times, the wind has been used as an energy source to pump water and for other purposes.

Since 1940 wind has been used – in limited applications – to produce electric energy. In 1940 the largest wind turbine of the time began operating on a Vermont hilltop known as Grandpa's Knob. This turbine, rated at 1.25 megawatts in winds of about 30 mph, fed electric power to the local utility network for several months during World War II.

The popularity of using energy in the wind has always fluctuated with the price of fossil fuels. When fuel prices fell after World War II, interest in wind turbines waned. But when the price of oil skyrocketed in the 1970s, so did worldwide interest in wind turbine generators.

The chart in Figure 3 on the next page shows the growth in wind energy production. Wind energy has grown from less than 15,000 gigawatt hours (GWH) in 2005 to over 454,000 GWH in 2024, which is an annual increase of over 19%!

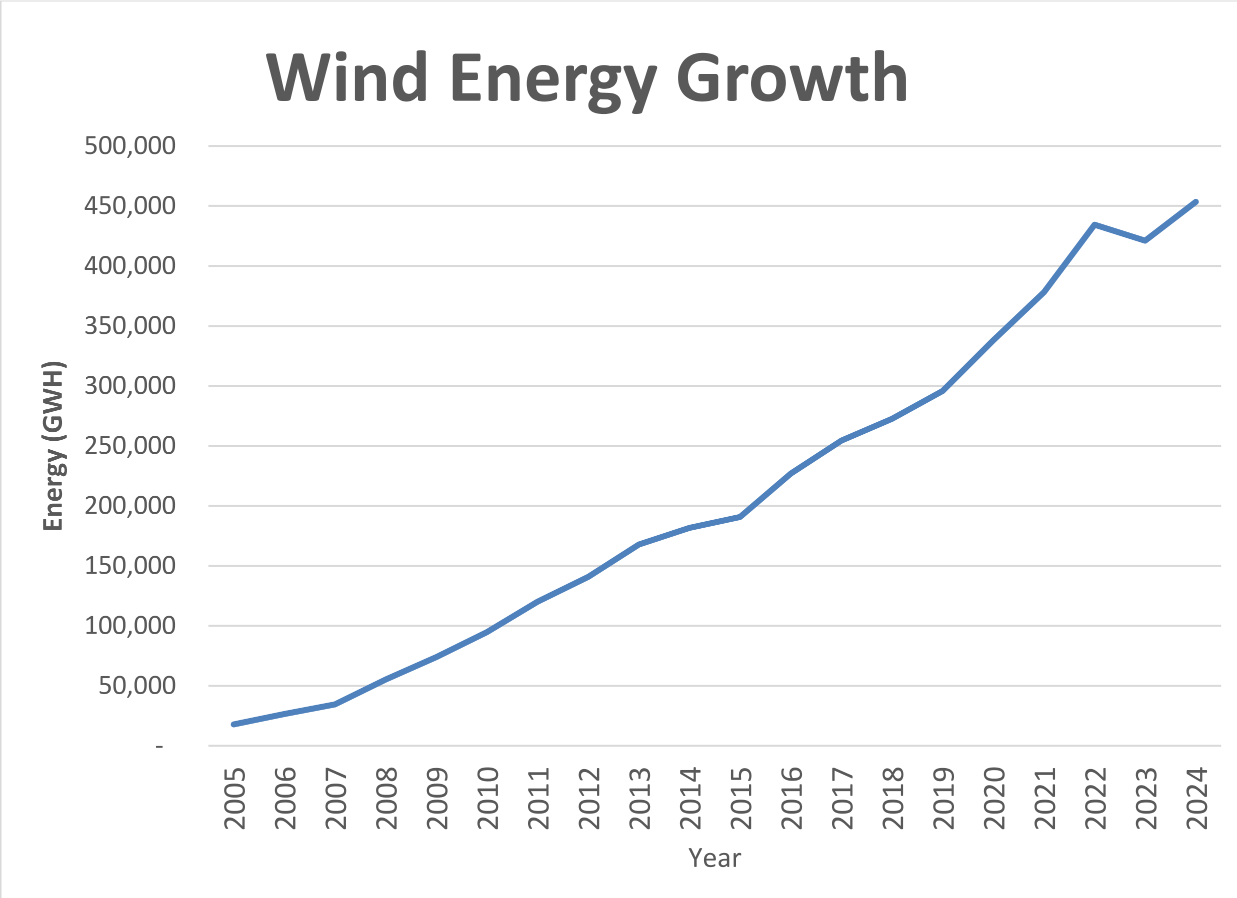


Figure 3

The wind turbine technology R&D that followed the oil embargoes of the 1970s refined old ideas and introduced new ways of converting wind energy into useful power. Many of these approaches have been demonstrated in "wind farms" or wind power plants — groups of turbines that feed electricity into the utility grid — in the United States and Europe.

Good wind areas, which cover 6% of the contiguous U.S. land area, have the potential to supply an amount of electricity equal to one and a half times the current electricity consumption of the United States. Of course, this does not mean that wind energy can be used to replace all other forms of electric energy generation. Wind is a variable energy resource and in practical applications will probably never be able to meet more than 20% of the nation's electric energy needs.

Estimates of the wind resource are expressed in wind power classes ranging from class 1 to class 7, with each class representing a range of mean wind power density or equivalent mean speed at specified heights above the ground. Areas designated class 4 or greater are suitable with advanced wind turbine technology under development today. Power class 3 areas may be suitable for future technology. Class 2 areas are marginal and class 1 areas are unsuitable for wind energy development.

The advantages of wind energy include,

- Wind energy is fueled by the wind, so it is a clean fuel source. Wind energy does not pollute the air like power plants that rely on combustion of fossil fuels, such as coal or natural gas. Wind turbines do not produce atmospheric emissions that cause acid rain or greenhouse gases.
- Wind energy is a domestic source of energy, produced in the United States.
- Wind energy relies on the renewable power of the wind, which cannot be used up. Wind is actually a form of solar energy; winds are caused by the heating of the atmosphere by the sun, the rotation of the earth, and the earth's surface irregularities.
- Wind energy is one of the lowest-priced renewable energy technologies available today.
- Wind turbines can be built on farms or ranches, thus benefiting the economy in rural areas, where most of the best wind sites are found. Farmers and ranchers can continue to work the land because the wind turbines use only a fraction of the land. Wind power plant owners make rent payments to the farmer or rancher for the use of the land.

There are disadvantages to the use of wind energy. A few of the disadvantages include,

- While the cost of wind power is getting more competitive, in most cases it is still not comparable with conventional generation.
- The major challenge to using wind as a source of power is that the wind is intermittent and it does not always blow when electricity is needed.
- Presently, storing wind energy is not practical and not all winds can be harnessed to meet the timing of electricity demands.
- Good wind sites are often located in remote locations, far from the load centers.
- Wind resource development may compete with other uses for the land, and those alternative uses may be more highly valued than electricity generation.
- Wind turbines can have a negative impact on aesthetics or “viewshed” of a community. This concern is especially prevalent in mountain areas where the residents do not want wind turbines to spoil their view.

In the next chapter we look at the components of a wind energy system and some of the associated operating characteristics. Then we will look at the wind resources in the United States, followed by a discussion of siting and interconnection of wind energy systems.

Chapter 1
Wind Turbine Designs

In this section we will look at the different types of wind turbines, the components that make up a wind turbine system, and a few of the operating characteristics of wind turbines.

Basic Designs

Modern wind turbines fall into two basic groups: the horizontal-axis variety and the vertical-axis design. The horizontal-axis units are what we typically think of when discussing wind turbines; they look like large airplane propellers mounted on a tower. An alternative is the vertical-axis unit, which is sometimes called a Darrieus wind turbine after the French inventor, Georges Darrieus. A horizontal-axis turbine and a vertical-axis, Darrieus wind turbine, are shown in Figure 4 below.

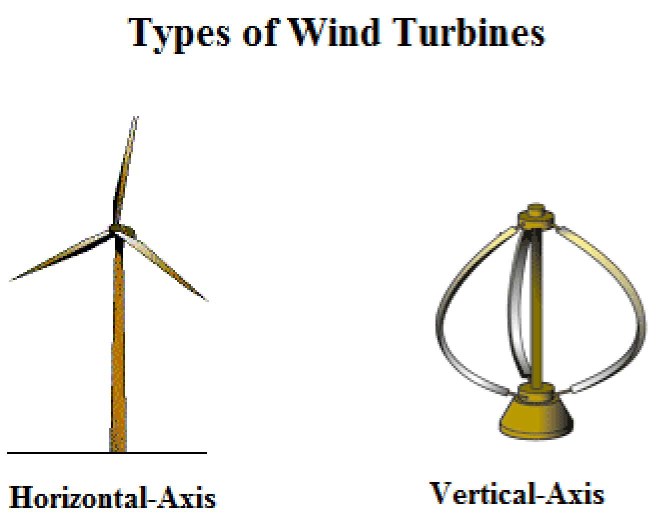


Figure 4

A horizontal-axis machine is the most common wind turbine design. A horizontal axis machine has its blades rotating on an axis parallel to the ground and parallel to the wind flow. These wind turbines can be operated either "upwind," with the blades on the wind side of the tower, or “downwind” with the blades on the lee side of the tower. In the upwind mode either a tail vane is required to keep the blades facing into the wind or a motor driven mechanism is used to control the direction of the turbine. In the “downwind” mode the wind passes the tower before striking the blades and even without a tail vane, the machine rotor naturally tracks the wind.

Vertical axis wind turbines are not as common as their horizontal-axis machines. The main reason for their lack of popularity is that they usually are situated at ground level and therefore cannot take advantage of the greater wind speeds at higher elevations where horizontal-axis machines operate. In addition to the *Darrieus* type of vertical-axis wind turbine, the *Giromill*, which has straight blades, and the *Savonius*, which uses scoops to catch the wind are also forms of vertical-axis machines. By design, a vertical axis machine does not have to be oriented with respect to wind direction and because the shaft is vertical, the transmission and generator can be mounted at ground level allowing easier servicing and a lighter weight, lower cost tower. Although vertical axis wind turbines have these advantages, their designs are not as efficient at collecting energy from the wind as are the horizontal machine designs.

System Components

The following figure shows the major components of a horizontal-axis wind turbine. Following the figure is a description of each of the components.

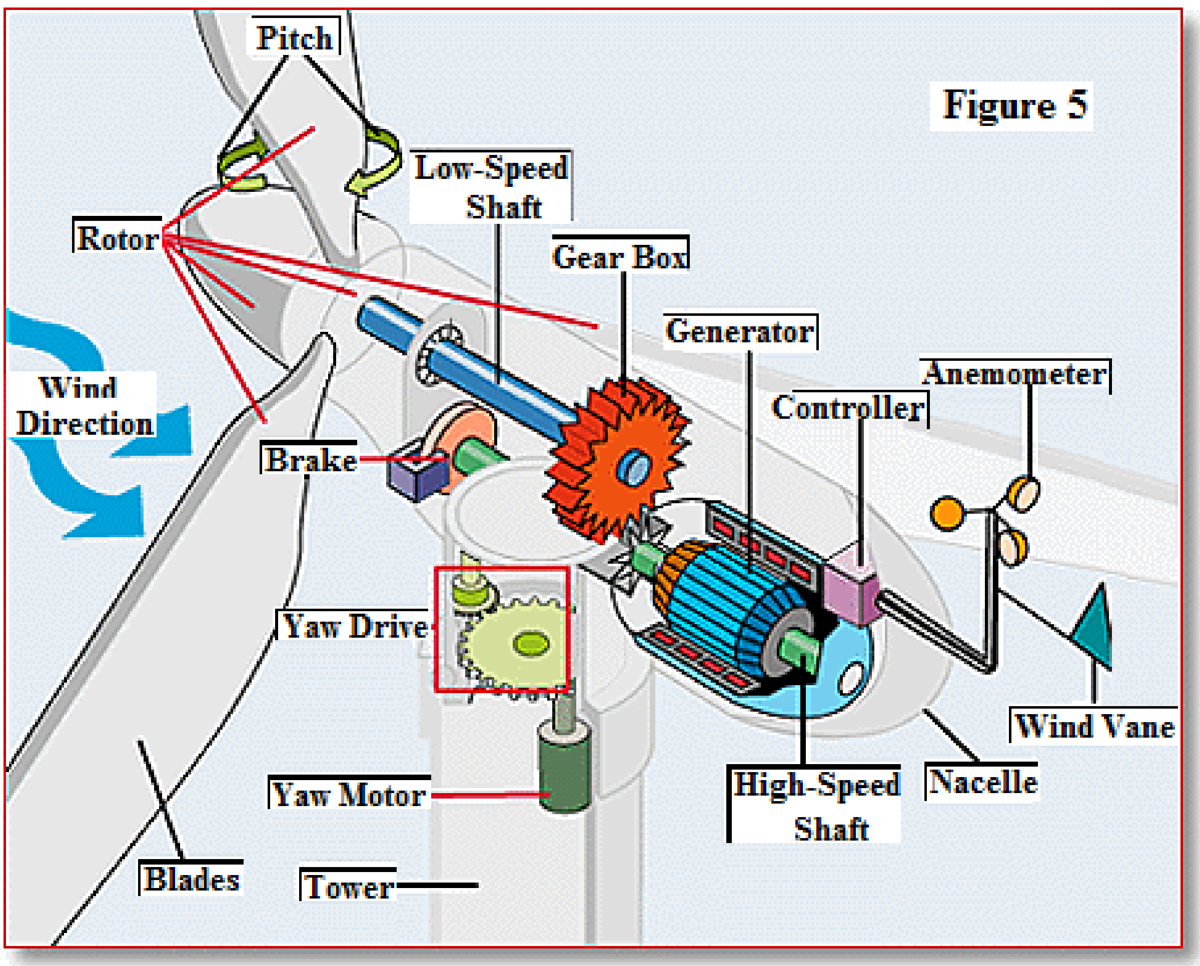


Figure 5

Anemometer
Measures the wind speed and transmits wind speed data to the controller.

Blades
Most turbines have either two or three blades. The blade design can be either a "drag" design or a "lift" design.

With a drag design blade, the wind pushes the blades out of the way. Drag powered wind turbines are characterized by slower rotational speeds and high torque capabilities. Drag blade designs are well suited for farm windmills, which must develop high torque at start-up to pump, or lift, water from a deep well. Dutch windmills also utilize drag design blades.

The lift blade design employs the same principle as aircraft airfoils. In fact, the blade is essentially an airfoil, or wing (Figure 6). When air flows past the blade, a wind speed and pressure differential is created between the upper and lower blade surfaces. The pressure at the lower surface is greater and thus acts to "lift" the blade. When blades are attached to a central axis, like a wind turbine rotor, the lift is translated into rotational motion. Lift-powered wind turbines have much higher rotational speeds than drag types and therefore are well suited for electricity generation.

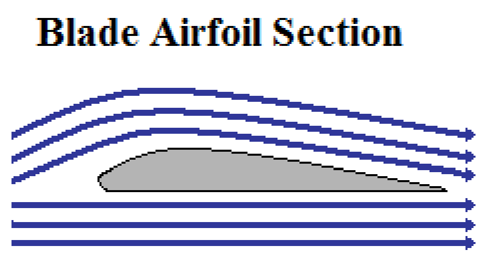


Figure 6

The tip-speed is the ratio of the rotational speed of the blade to the wind speed. The larger this ratio, the faster the rotation of the wind turbine rotor at a given wind speed. Electricity generation requires high rotational speeds. Lift-type wind turbines have maximum tip-speed ratios of around 10, while drag-type ratios are approximately 1.

The number of blades that make up a rotor and the total area they cover affect wind turbine performance. For a lift-type rotor to function effectively, the wind must flow smoothly over the blades. To avoid turbulence, spacing between blades should be great enough so that one blade will not encounter the disturbed, weaker air flow caused by the blade which passed before it. It is because of this requirement that most wind turbines have only two or three blades on their rotors.

Brake
A disc brake is used to stop the rotor in emergencies. The brake can be applied mechanically, electrically, or hydraulically.

Controller

The controller starts up the machine at wind speeds of around 10 miles per hour (mph) and shuts off the machine at the "cut-out" speed. Because of the potential to damage the machines, turbines do not operate at high wind speeds.

Gear box

Most wind turbines require a gear-box transmission to increase the rotation of the generator to the speeds necessary for efficient electricity production. Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1,000 to 1,800 rpm, which is the rotational speed required by most generators to produce electricity.

Some DC-type wind turbines do not use transmissions. Instead, they have a direct link between the rotor and generator. Without a transmission, wind turbine complexity and maintenance requirements are reduced, but a much larger generator is required to deliver the same power output as the AC-type wind turbines.

Generator

The generator converts the turning motion of wind turbines blades into electricity. The generator can be either an alternating current (AC) or direct current (DC) unit. There are many different output ratings, and they are sized for the size of the wind turbine blades. For commercial applications, the most common type of generator is an induction generator that produces 60-cycle AC electricity.

The induction generators are almost always adjustable speed drives because they reduce mechanical stresses by storing the energy from wind pulses in the mechanical inertia of the turbine. In some applications, the adjustable speed drive converters can be used to supply reactive power. The generators are usually one of the following types: squirrel-cage induction generator, wound-rotor induction generator, doubly fed asynchronous generator, or synchronous generator.

A *squirrel-cage induction generator* has a gearbox to match the rotational speed of blades with that of the generator. Mechanical power is regulated through an inherent aerodynamic stall characteristic of blades or with active control of blade pitch.

A *wound-rotor induction generator* has a gearbox for coupling the electrical generator to the rotor hub. They also have pitch control of blades for maximizing energy capture and controlling turbine speed within range of the generator and a small range of variable speed operation.

A *doubly fed induction generator* is an induction generator with a wound rotor and a four quadrant AC-to-AC converter, which is connected to the rotor winding. It has a variable frequency excitation of the rotor circuit, incorporating rotor current control via power converter. The rotor circuit power converter may be four-quadrant, allowing independent control of real and reactive flow in either direction (rotor to grid or grid to rotor), or confined to unidirectional (grid to rotor) real power flow. These machines have a gearbox for coupling the generator shaft to turbine hub, active control of turbine blade pitch for maximizing production and controlling mechanical speed, and variable speed operation depending on the rating of power converter relative to turbine rating

A *synchronous induction generator* has the generator coupled to the grid through a fully rated ac/dc/ac power converter. They have a gearbox to match generator speed to variable rotational speed of blades and variable speed operation over a wide range, depending on electrical generator characteristics.

High-speed shaft
The high-speed shaft is connected to the low-speed shaft by the gear box and drives the generator. The high-speed shaft will turn at between 1,000 and 1,800 rpm.

Low-speed shaft
The low-speed shaft is connected directly to the rotor hub. The rotor turns the low-speed shaft at about 30 to 60 rotations per minute.


Photo Credit: DOE/NREL

Nacelle
The nacelle sits atop the tower and contains the gear box, low- and high-speed shafts, generator, controller, and brake.

Pitch
Blades are turned, or pitched, out of the wind to control the rotor speed and keep the rotor from turning in winds that are too high or too low to produce electricity.

Rotor
The blades and the hub together are called the rotor. The blades are attached to the hub, which is attached to the low-speed shaft.

Tower
Towers are made from tubular steel (such as shown in the figure), concrete, or steel lattice. The tower on which a wind turbine is mounted is not just a support structure. It also raises the wind turbine so that its blades safely clear the ground and so it can reach the stronger winds that are

found at higher elevations. Larger wind turbines are usually mounted on towers ranging from 120 to 210 feet in height.

Wind direction
The turbine shown in figure 5 is an "upwind" turbine, so-called because it operates facing into the wind. Other turbines are designed to run "downwind," facing away from the wind.

Wind vane
The wind vane measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

Yaw drive & motor
Upwind turbines face into the wind; the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines do not require a yaw drive; the wind blows the rotor downwind. The yaw motor powers the yaw drive.

Operating Characteristics

A few of the important operating characteristics of a wind turbine include the cut-in speed, rated speed, cut-out speeds, power output, and capacity factor.

Cut-in Speed
There is a minimum speed at which a wind turbine can reliably produce useable power. This is known as the *cut-in speed* and for modern wind turbines is generally around 10 mph.

Rated Speed
The *rated speed* is the minimum wind speed at which the wind turbine will generate its designated rated power. For example, a 2.5 MW wind turbine will typically only produce its rated power once the wind speed exceeds about 27 mph. Most wind turbines are rated at between 25 and 35 mph. At wind speeds between cut-in and rated, the power output from a wind turbine increases as the wind increases. The power output of a wind turbine is relatively flat above its rated speed until the wind speed reaches the cut-out speed. The graph shown in Figure 7 is an example of a power curve for a wind turbine.

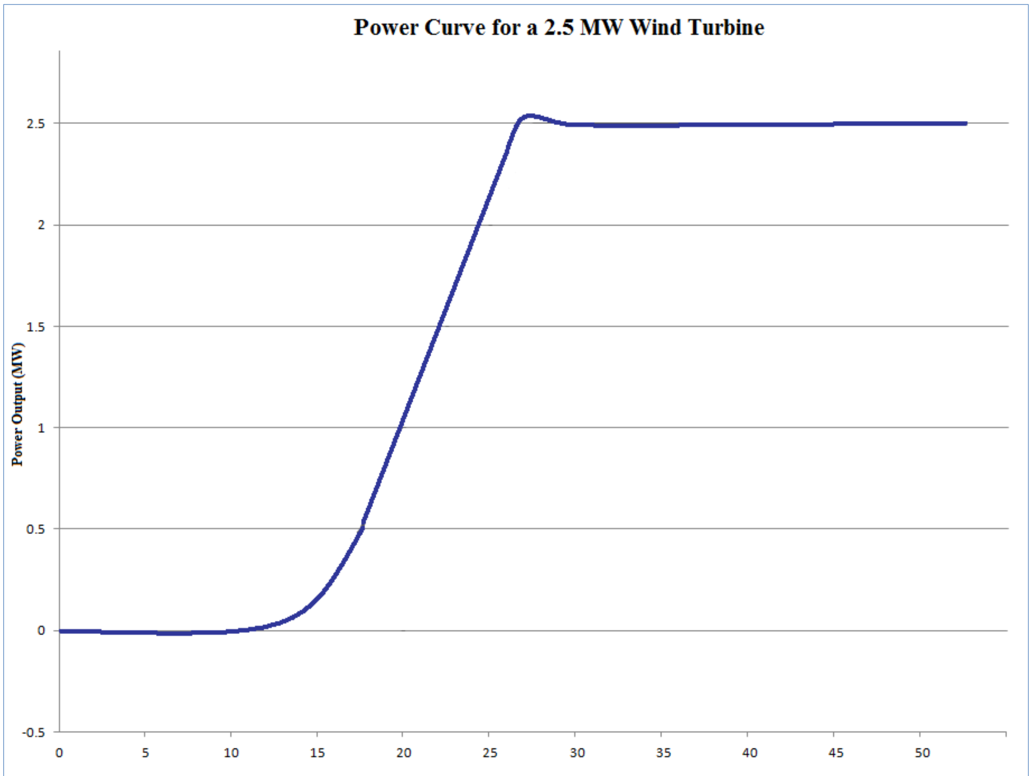


Figure 7

Cut-out Speed

Above a certain speed, the wind turbine will need to shut down and cease operation to prevent damage to the unit. Cut-out speeds vary by manufacturer from about 45 to 60 mph. The wind speed at which shut down occurs is called the *cut-out speed*. The most common method of shutting down a wind turbine is for the blades to change pitch so that the wind just passes through the blades without producing lift. Other methods include turning the units parallel to the wind or the use of some type of drag device that prevents the blades from turning in the high winds.

Betz Limit

It is impossible for the blades of a wind turbine to be 100% efficient since some of the wind energy must pass through the blades to make the turbine turn. Air flowing over the blades and through the rotor area makes a wind turbine function. The wind turbine extracts energy by slowing down the wind. The theoretical maximum amount of energy in the wind that can be collected by a wind turbines rotor is approximately 59%. This value is known as the Betz limit. If the blades were 100% efficient, a wind turbine would not work because the air, having given up all its energy, would entirely stop. Considering the Betz limit and the efficiency losses through the generator, gearbox, etc., will result in only about 15-25% of the wind energy being converted into useful power.

Power Output

The power generated by a wind turbine can be found using the following formula,

$$\mathbf{P = 0.5 * \rho * A * Cp * Ng * Nb * V^3}$$

Where,
P = Power produced by the generator, watts.
ρ = Air density, kg/m^3
A = Swept area of the blades, m^2.
Cp = Coefficient of performance of the blades/
Ng = Generator efficiency.
Nb = Gearbox efficiency.
V = wind speed, meters/sec.

Simplifying and converting to English units, the power equation can be approximated as,

$$\mathbf{P = 0.004167 * Cp * Ng * Nb * D^2 * V^3}$$

Where,
D = Diameter of the blades, feet.
V = Wind speed, mph.

Example. Consider a wind turbine with 20-foot diameter rotor, a coefficient of performance of 0.30, generator efficiency of 0.8, a gearbox efficiency of 0.90, and a wind speed of 25 mph. What is the expected power output in watts?

$P = 0.004167 * 0.30 * 0.80 * 0.90 * 20^2 * 25^3$

P = 5,625 watts, or 5.625 kW.

Capacity Factor

The capacity factor of a wind turbine is actual energy output of a wind turbine during a given time period, usually one year, compared to its theoretical maximum energy output. The capacity factor is,

$$\mathbf{CF = \frac{kWh\ produced}{8{,}760 * Rating_{Nameplate}}}$$

Where,
CF = Capacity factor.
kWh produced = Energy produced during the year based on actual or expected winds.
Rating = Nameplate rating of the wind turbine, kW.

Example. A 2.5 MW wind turbine could conceivably produce 21,900,000 kWh's per year (2.5 * 1,000 * 8760). However, due to the variability of the wind the unit will likely produce 5,000,000 kwh per year. In this example, the capacity factor is,

$$CF = \frac{5{,}000{,}000}{8{,}760 * 2{,}500}$$

$$CF = 22.8\%$$

Typically, wind turbines have capacity factors of between 20-35% for units located with good wind capacity.

Chapter 2
Wind Resources

Wind is a by-product of solar energy. Sunlight reaching the surface of the earth causes heating of the surface. Because of the irregularity of the earth's surface (deserts, forests, cities, etc.) it heats and cools unevenly, which creates pressure differentials around the globe. With these pressure differentials, the air surrounding the earth will try to move from areas of high pressure to "fill-in" the areas of low pressure. It is estimated that approximately two percent of the sun's energy reaching the earth is converted into wind energy.

In some areas of the world the wind is fairly constant, such as along some coastlines and around islands in the oceans. In the interior of the United States, the winds are much less constant – and highly variable - since it is a function of frontal boundaries between pressure systems. Generally, winds in the interior of the United States are strongest during the winter, spring, and summer and lightest during the summer. On a daily basis, winds tend to be strongest in late afternoon and lightest early in the morning. This variability is one of the biggest drawbacks to wind energy use for the production of electricity.

For a wind energy generator to be cost effective the amount of wind and the consistency must be considered when siting a turbine.

Wind Speed versus Wind Power

Wind speed is the rate at which air flows past a point above the earth's surface. Wind speed can be quite variable and is determined by a number of factors including height, geography, obstruction, and location. *Wind power* is a measure of the energy available in the wind. It is a function of the wind speed cubed (V^3). Therefore, a doubling of the wind speed will increase the wind power by a factor of eight. Because of this relationship, small differences in wind speed can have a dramatic impact on the wind power available.

Wind power density is the value of choice for wind analysis because the wind power density value combines the effect of the distribution of wind speeds and the dependence of the power density on air density and on wind speed. *Wind power density* is described by the wind power available per unit area swept by the blades and is normally expressed in metric units which are watts per square meter (W/m^2).

Because of the wind's normal variability, and the effect of this variability on the cube of the wind speed, the power equation should only be used for instantaneous or hourly wind speeds and not for long-term averages. As an example, let us compare the difference in wind energy density for a location where the wind blows at a constant 10 mph year-round and a location where the wind blows 20 mph for six months and does not blow at all for the other six months. In both cases the average wind speed is 10 mph. Assuming that the wind turbines have the same characteristics at both locations and for the given characteristics the power equation is,

$$\mathbf{P = 0.05 * V^3}$$

For the first location the energy density is,

$P = 0.05 * 10^3$

$P = 50 \text{ w/m}^2$

In the second location the energy density is,

$P_{20} = 0.05 * 20^3$

$P_{20} = 400 \text{ w/m}^2$

$P_0 = 0.05 * 0^3$

$P_0 = 0 \text{ w/m}^2$

$P_0 + P_{20} = (400 + 0)/2 = 200 \text{ w/m}^2$

As you can see, the location where the wind blows at 20 mph for six months and does not blow at all for the other six months still has more energy than the location with a constant 10 mph wind, even though the average wind is the same in both locations. With the constant wind, the wind energy density is 50 W/m^2, but at the location with a varying wind the wind energy density is 200 W/m^2, or four times the location with the constant wind. And in both cases, the average wind speed is 10 mph.

Wind Power Classes

Wind resources for wind energy is defined based on the power density of the wind and is divided into one of seven *wind power classes*. Each wind power class represents the range of wind power densities likely to be encountered at exposed sites within an area designated as having that wind power class. Table 1 gives the power density limits for the wind power classes used for the 33-ft (10-m) and 164-ft (50-m) reference levels.

Table 1
Wind Power Class

Wind Power Class	33ft (10m)		164 ft (50m)	
	Power Density (W/m^2)	Speed (mph)	Power Density (W/m^2)	Speed (mph)
1	0 – 100	0 – 9.8	0 – 200	0 – 12.5
2	100 – 150	9.8 – 11.5	200 – 300	12.5 – 14.3
3	150 – 200	11.5 – 12.5	300 – 400	14.3 – 15.7
4	200 – 250	12.5 – 13.4	400 – 500	15.7 – 16.8
5	250 – 300	13.4 – 14.3	500 – 600	16.8 – 17.9
6	300 – 400	14.3 – 15.7	600 – 800	17.9 – 19.7
7	400 - 1,000	15.7 – 21.1	800 – 2,000	19.7 – 26.6

Wind power density is proportional to the third moment of the wind speed distribution and to air density; therefore, a unique correspondence between power density and mean wind speed (the first moment of the speed distribution) does not exist.

However, by specifying a Rayleigh wind speed distribution and a standard sea level air density a mean wind speed can be determined for each wind power class limit. The decrease of air density with elevation requires the mean Rayleigh speed to increase by about one percent per 1,000 feet elevation to maintain the same wind power density. If the wind speed distribution is more sharply peaked than the Rayleigh distribution, the equivalent mean wind speed will be slightly higher than the value in Table 1. Conversely, a broader distribution of wind speeds will slightly reduce the equivalent mean speed.

Rayleigh wind speed distribution
Rayleigh distribution is a continuous probability distribution. It usually arises when a two-dimensional vector (e.g., wind velocity) has its two orthogonal components normally and independently distributed. The absolute value (e.g., wind speed) will then have a Rayleigh distribution.

Figure 8 shown below is a large-scale view of the wind power classes in the United States.

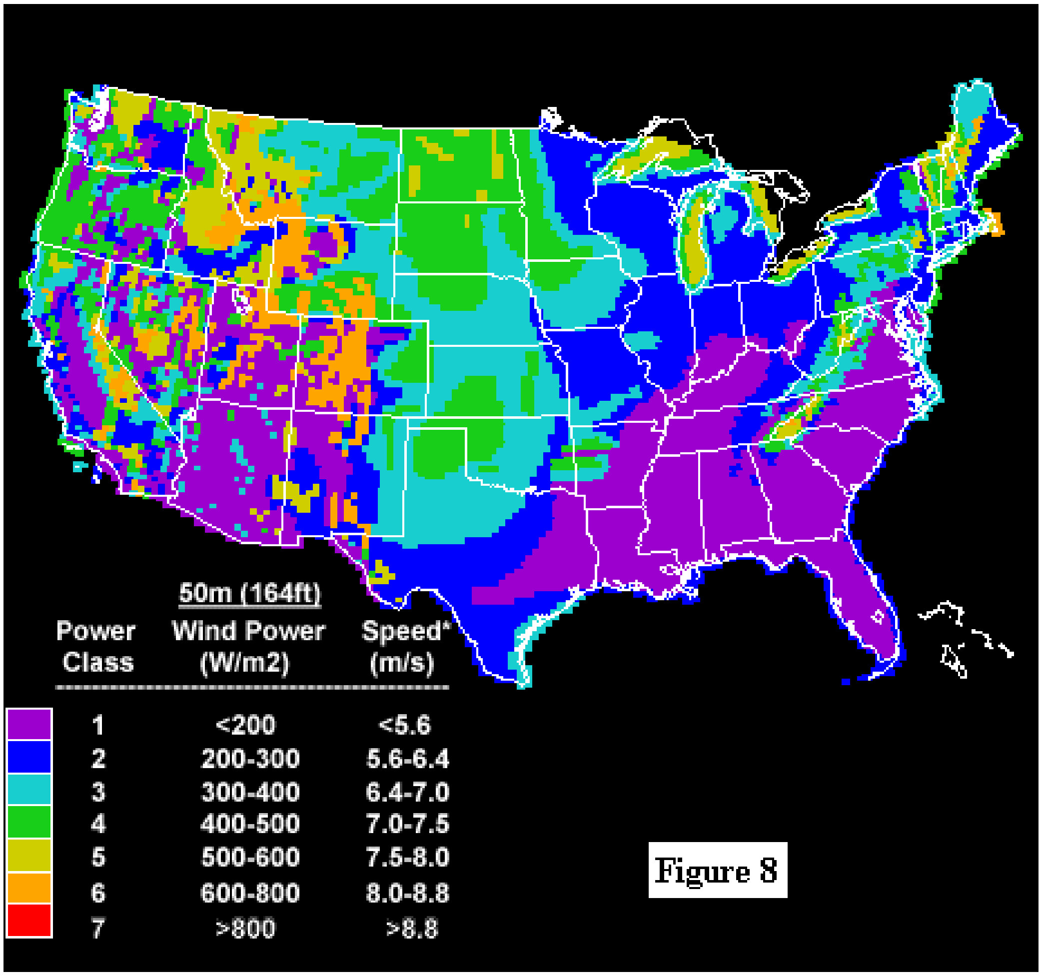


Figure 8

As you can see in this figure, the Southeast is predominately a wind power class of 1, while most of the coast of Oregon has a wind power class of 4. North and South Dakota also have large areas with a wind power class of 4 or more.

The next figure shows a more detailed view of a portion of Wyoming with the wind power classes defined into small geographic areas. As you can see from this diagram, there is an exceptionally good wind resource in the Rocky Mountains with a wind power class of 6. Also, around Laramie, Wyoming are areas of wind power class 5 and 6.

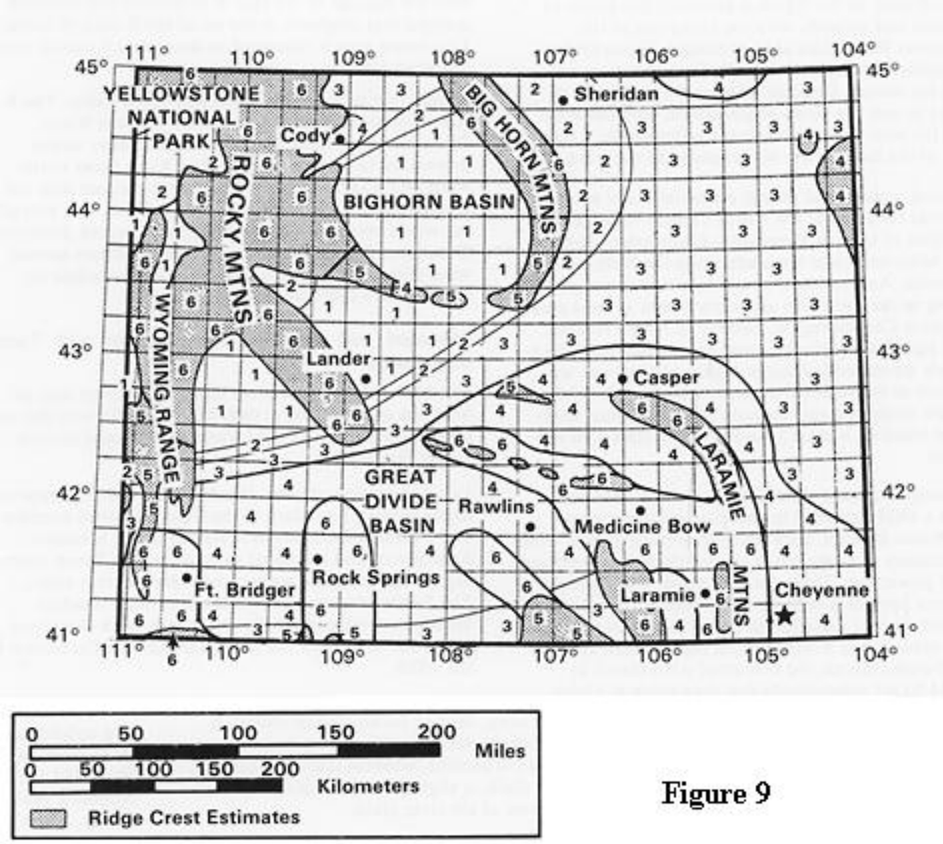


Figure 9

Generally, areas designated as a wind power class of 4 or greater are suitable with advanced wind turbine technology under development today. A wind power class of 3 may be suitable for future technology. Areas with a wind power class of 2 are marginal and class 1 areas are unsuitable for wind energy development.

Classes of Land-Surface Form

The physical characteristics of the land-surface form affect the number of wind turbines that can be sited in exposed places. For example, over 90% of the land area in a flat plain may be favorably exposed to the wind. However, in mountainous terrain only the ridge crests and passes, which may be only a small percentage of the land area, may represent exposed sites. Publications such as the Wind Energy Resource Atlas of the United States use land-surface form data to describe the percentage of areas that are potentially suitable for wind energy systems.

The map of classes of land-surface form provides information on the distribution of plains, tablelands, hills, and mountains in the United States.

For each class of land-surface form, the percentage of land area that is representative of well exposed, moderately exposed, and poorly exposed sites has been estimated. These percentages were determined subjectively as a function of the slope, local relief, and profile type. Table 2 gives the average percentage of land area that is designated as exposed terrain for the different classes of land-surface form.

Table 2
Land Surface Forms

Land-Surface Form	Exposed Feature (Map Value)	Percentage Area
Plains	Plains	93
Plains with Hills	Open plains	79
Plains with Mountains	Plains Ridge crests & mountain summits	67 10
Tablelands	Tablelands, uplands	80
Open Hills	Hilltops, uplands	27
Open Mountains	Broad Valleys Ridge crests & mountain summits	80 12
Hills	Hilltops, uplands	9
Mountains	Ridge crests & mountain summits	3

As you can see in Table 2, plains in the United States have 93% of their land area exposed to the wind. In comparison, in mountainous areas only about 3% of the land area is exposed.

The values in Table 2 are for the Northwest region of the United States. There are slight variations in these average percentages from region to region.

Certainty Rating

The analyses of wind power density at exposed sites shown on wind power maps depend on the subjective integration of several factors: quantitative wind data, qualitative indicators of wind speed or power, the characteristics of exposed sites in various terrains, and familiarity with the meteorology, climatology, and topography of the region. As a result, the degree of certainty with which the wind power class can be specified depends on:

- The abundance and quality of wind data
- The complexity of the terrain
- The geographical variability of the resource

A certainty rating, from 1 (low) to 4 (high), of the wind energy resource estimate has been made for each grid cell of a ¼° latitude by 1/3° longitude grid over the contiguous U.S. by considering the influence of the above three factors on the certainty of the estimate of the wind power class. Different sized grid cells were used for the other regions. The certainty ratings have been digitized for each grid cell in the United States.

The certainty ratings for the wind resource assessment are defined as follows:

Rating 1 - The lowest degree of certainty

A combination of the following conditions exists:

- No data exist in the vicinity of the cell.
- The terrain is complex.
- Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.

Rating 2 - A low-intermediate degree of certainty

One of the following conditions exists:

- Few or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data.
- Limited data exist in the vicinity of the cell, but the terrain is complex, or the mesoscale variability of the resource is large.

Rating 3 - A high-intermediate degree of certainty

One of the following conditions exists:

- There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data.
- Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.

Rating 4 - The highest degree of certainty

Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.

The assignment of a certainty rating requires subjective evaluation of the interaction of the factors involved.

Impact of Elevation on Wind Speed

Elevation affects wind speed, and the wind is generally stronger at higher elevations due to less influence from surface obstructions such as trees and buildings. These obstructions also create turbulence, which disrupts the air flow to a wind turbine.

At higher elevations, surface irregularities have less impact on the wind, which means wind speeds will generally be higher. While only an estimate, the following formula can be used as an approximation of wind speed at different heights.

$$\mathbf{V_2 = V_1 * \left(\frac{H_2}{H_1}\right)^{\alpha}}$$

Where,
V_1= Wind speed at a height_1, mph.
V_2= Expected wind speed at a given height_2, mph.
H_1 = Height of a given wind, feet.
H_2 = Height of an unknown wind speed, feet.
α = Hellman exponent, see table 3.

Table 3 Hellman Exponent	
Location	**α**
Above flat open coast	0.16
Above open water surface	0.27
Above human inhabited areas	0.34
Note: This is an abbreviated version of the factors and surface conditions.	

Example. What is the expected wind speed at 150 feet, if the wind speed at 50 feet is measured to be 10 mph over an inhabited area?

$$V_{150} = 10 * \left(\frac{150}{50}\right)^{0.34}$$

$$V_{150} = 14.5 \text{ mph.}$$

So, the wind at 150 feet should be about 15 mph versus 10 mph at 50 feet.

This method only provides a rough estimate of wind speeds and is not a precise value. It is most useful when using average and not instantaneous wind speeds. In addition, this formula should only be used for relatively flat terrain because hills and mountains often have unpredictable influences on wind characteristics.

Wind Resources in the United States

The National Energy Renewable Energy Laboratory has published maps of the United States showing the potential wind energy density in the country. The maps are compiled in the Wind Energy Resource Atlas of the United States.

The production of mean wind power density maps depends on the coherent synthesis of several pieces of information. The goal of the synthesis process is to present wind power density values representative of sites that are well exposed to the wind. Hilltops, ridge crests, mountain summits, large clearings, and other locations free of local obstructions to the wind are naturally expected to have good exposure to the wind. As you would expect, locations in narrow valleys and canyons, downwind of hills and obstructions, or in forested or urban areas are likely to have poor exposure. The wind power density shown on the maps in this atlas is a fairly conservative estimate of the wind resources in exposed areas such as mountain ridges and summits. It, however, is not very representative of poorly exposed locations.

Although approximately 3,000 stations provided the wind resource assessment of the United States with quantitative data, these stations were not uniformly distributed. Most of the stations are located in populated areas and along transportation corridors. Large areas in the United States are devoid of any form of quantitative wind data suitable for this assessment. Furthermore, in mountainous areas, most observation sites are confined to valley locations. To evaluate the distribution of the wind resource in data-sparse areas, three qualitative indicators of the wind speed or power are used. These include topographic, wind-deformed vegetation, and eolian landforms.

Topographic Indicators

The most widely used technique depended on certain combinations of topographical and meteorological features that are associated with high or low wind speeds. The features indicative of high mean wind speeds are:

- Gaps, passes, and gorges in areas of frequent strong pressure gradients
- Long valleys extending down from mountain ranges
- High elevation plains and plateaus
- Plains and valleys with persistent strong down slope winds associated with strong pressure gradients
- Exposed ridges and mountain summits in areas of strong upper-air winds
- Exposed coastal sites in areas of strong upper-air winds or strong thermal/pressure gradients

Features that signal rather low mean wind speeds are:

- Valleys perpendicular to the prevailing winds aloft
- Sheltered basins
- Short and/or narrow valleys and canyons
- Areas of high surface roughness, e.g., forested hilly terrain

Because of geography that includes hills, valleys, river bluffs and lakes, a complex and highly variable wind regime is created. Trees and buildings add to the complexity of the wind on a smaller scale. Each geographical feature influences wind flow.

Hills, plateaus, and bluffs provide good elevations with potentially high wind speeds. Valleys, which are lower and sheltered, generally have lower wind speeds. However, all valleys are not necessarily poor wind sites. When oriented parallel to the wind flow, valleys may channel and improve the wind resource. A constriction to the valley may further enhance wind flow by funneling the air through a smaller area. This is often the case in narrow mountain passes or gaps that face the wind.

Valleys often experience calm conditions at night even when adjacent hilltops are windy. Cool, heavy air drains from the hillsides and collects in the valleys. The resulting layer of cool air is removed from the general wind flow above it to produce the calm conditions in the lowlands. Because of this, a wind turbine located on a hill may produce power all night, while one located at a lower elevation stands idle. This phenomenon is more likely to occur on high terrain features that reach at least several hundred feet above the surrounding land.

High terrain features can accelerate the flow of wind. An approaching air mass is often squeezed into a thinner layer, so it speeds up as it crosses the summit. Over a ridge, maximum acceleration occurs when the wind blows perpendicular to the ridge line. Isolated hills and mountains may accelerate the wind less than ridges because more of the air tends to flow around the sides. The downward, or "lee," side of high terrain features should be avoided because of the presence of high wind turbulence. See the figure below (Figure 10) for an illustration of the effects of terrain on turbulence.

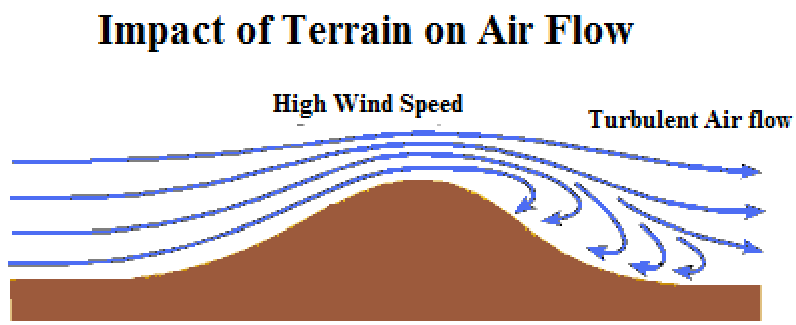
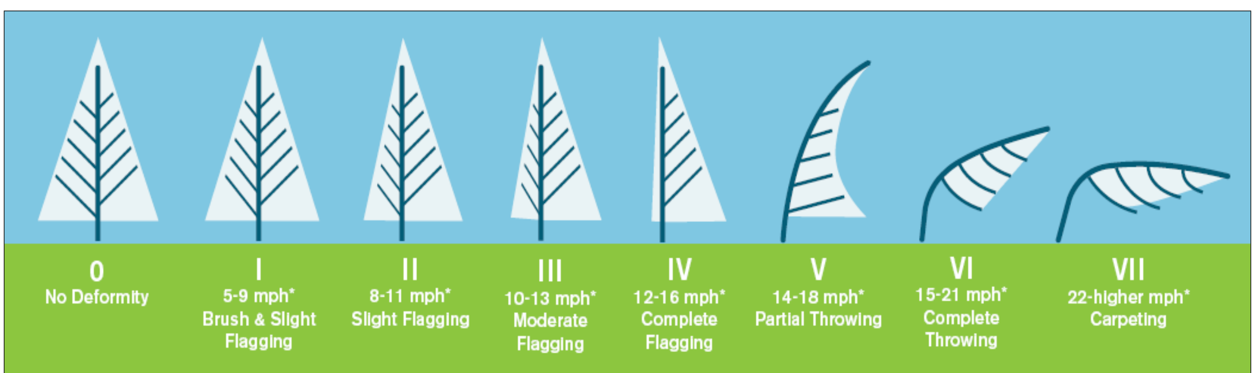


Figure 10

Land areas adjacent to large bodies of water may be good wind sites for two reasons. First, the water surface is much smoother than a land surface, so air flowing over water encounters little friction. The best shoreline site is one where the prevailing wind direction is "onshore." Second, when regional winds are light, as on a sunny summer day, local winds known as sea or lake breezes can develop because the land and water surfaces heat up at different rates. Because land heats more quickly than water, the warm rising air over the land is replaced by the cooler air from over the water. This produces an onshore breeze of typically 8 to 12 mph or more. At night, the breeze stops or reverses direction, as the land cools more quickly.

Wind-Deformed Vegetation

Evidence of strong persistent winds can also be found in wind-deformed vegetation. Mean wind speeds can be deduced from the extent of such deformation on trees and shrubs. However, there are a number of practical limitations to the use of trees as indicators of mean wind speed.



Griggs-Putnam Index. *Probable mean annual windspeed. Data prepared by E.W. Hewson, J.E. Wade, and R.W. Baker of Oregon State University

Figure 11

The illustration shown in Figure 11 above is known as the Griggs-Putnam Index and it attempts to use vegetation deformation as an indicator of wind speeds and has eight levels of wind deformation. At level "0", no deformation is present, and the wind is assumed to be less than 5 mph. At a wind speed of 12-16 mph (level IV) the vegetation on a plant or tree will be completely "flagged", or brushed to one side of the tree, but the tree trunk does not exhibit any deformation. At a level VII, the vegetation is said to be "carpeted" and completed blown in the downwind direction including the tree trunk as well as the branches.

Although wind-flagged trees may indicate that the mean wind speeds are strong, trees that are un-flagged do not indicate that the winds are light. There may be locations where strong winds come from several directions, and persistence from any one direction is insufficient to cause wind flagging. Nevertheless, in spite of the possible errors that are inherent in use of trees as an indicator of mean annual wind speed, they are useful in identifying potential areas with moderate-to-high wind resources.

Trees growing in an area of high winds are often permanently deformed. Severe deformation, such as when the tree trunk is bent away from the prevailing wind direction, occurs at wind speeds of 14 to 18 mph. However, "brushing" or "flagging" can be seen in a tree exposed to average speeds as low as 8 to 11 mph when the wind prevails from one dominant direction. An examination of the vegetation in an area can be a rough indicator of the wind strength there.

Brushing is common in deciduous trees, like maple, oak, and elm, where the branches and twigs bend downward like the fur of a pelt that has been brushed in one direction. Flagging is common in coniferous trees, like pine and spruce. It is indicated by branches that stream downwind and by short or missing upwind branches.

The absence of deformation does not necessarily imply that the wind resource is weak. Some tree species are more sensitive to the wind than others. Trees within a continuous forest, for example, are sheltered, and strong winds may blow from more than one major direction. Because of the above-mentioned concerns, many believe that wind-deformation should only be considered a crude indicator of wind resources.

Aeolian Landforms

An *Aeolian process* is the ability of wind to shape the surface of the Earth. Winds erode, transport, and deposit materials, and are effective agents in regions with sparse vegetation and a large supply of unconsolidated sediments. Although water is much more powerful than wind, aeolian processes are important in arid environments such as deserts.

The removal and deposition of surface materials by the wind to form playas, sand dunes, and other types of aeolian landforms indicate strong winds from a nearly constant direction. However, correlating characteristics of aeolian features to long-term mean wind speeds has proven difficult.

Chapter 3

Siting and Interconnection

Some of the greatest obstacles to more wind generation are finding suitable environmental locations to install the units and finding locations with adequate electrical infrastructure to transport the wind power to the load centers. Other concerns include integrating the operational characteristics of wind power into the operations practices of the electric utilities.

Utility Issues

Transmission access is a formidable problem for wind generation. Wind generation tends to be installed in very remote locations. But the amount of power generated from a wind farm, maybe 50 megawatts, will require a high voltage transmission line to transport the power from the wind farm to a point of interconnection to the electric grid. The electric grid may be miles from the wind farm though. The cost of transmission is considerable. An 115 kV transmission line may cost one million dollars per mile or more to construct. A five-mile transmission line will require an investment of five million dollars just to transport the power to the grid.

Even though a wind farm can be built fairly quickly it can take years to build a transmission line due to permitting, easement acquisition (including, in some cases, condemnation of property), and construction.

Another concern of electric utilities when adding wind resources to their generation mix is the variability of the output due to the wind. This condition is sometimes referred to as wind intermittency, but in reality, the wind is not so intermittent as it is variable. A better word for wind availability is variability because wind is variable. Even though it is variable, it is somewhat predictable, and wind forecast can give a good idea of the wind availability for some time in the future (e.g., the next hour or the next day's wind forecast.)

Electric generation and consumption occur in real-time; there is no significant ability to store energy for later use in a large-scale utility application. Therefore, generation resources must always be 'on-line' and ready for consumption by the end-user. This is a problem for wind generation because the wind may not be blowing when the demand for electricity is present. To compensate for the variability of the wind, utilities must have other resources available for the times that the wind is not available. Studies have shown that at low penetrations of wind resources, the cost of reserves or back up power for wind resources is insignificant because of the variability of the loads themselves as well as the other generation reserves already available. As the percentage of wind energy grows the cost of providing reserves for wind energy grows too.

The variability of the output of a wind farm is time dependent. The output of a wind farm will vary little from second to second. It will have more variability from minute to minute and even greater variability from hour to hour.

Based on where a wind farm is sited, the reserves may become a problem at penetrations as low as 5%, but in most areas, it is believed that utilities can tolerate wind energy production of up to 20% of their total generation without creating a major problem.

The cost impact of wind energy on a utility's operations is subject to debate, but studies have shown that at penetrations less than five percent, the cost impact is less than 4 mills per kWh ($0.004 per kWh) and at penetrations of 20% the cost impact is likely 9 mills per kWh.

To understand the impact of a wind turbine on a utility's generation operation, we must first understand how electric generation is scheduled. There are three time periods to consider when discussing utility generation. The periods are defined as unit commitment, load following, and regulation.

Unit commitment is the longest time period and can range from one day to one week and is defined in one-hour increments. Unit commitment is based on the time needed to start and stop a generating plant so that it is online and available when needed. For instance, a coal plant may take 1-2 days to get up to full output, and a nuclear plant may take several days to reach full output. Whereas a combustion turbine can be started and reach full output within 15 minutes. The utility system operator must look at the weekly weather forecasts and anticipated demand on the electric system for the next few days and decide which units to commit to meet the load. He may need to make these commitments several days in advance to have the units ready when needed. Once a unit is committed it most likely will need to run for several days to make its startup and use economically feasible. It is not practical to spend 24-36 hours starting up a coal plant to only use it for a few hours before shutting down again.

Load following is a period of one-hour to several hours and is defined in 5-to-10-minute intervals. The electric load on a power system varies throughout the day. During the summer, there is generally a steady increase in power consumption starting in the morning and growing throughout the day until early evening when the load will begin to subside (unless summer afternoon thunderstorms move in and cool the atmosphere down, creating a sharp drop in demand during the afternoon hours.) During this time period the system operator must make real-time decisions to increase or decrease the output of generating units to meet the demands for the next hour. If a unit commitment was previously made to run a coal plant, then the operator has the flexibility to ramp the output of the plant up or down to meet the changing load conditions.

Regulation is a time period of one minute to one hour and is in one to five second increments. Regulation is accomplished by an automatic generation control (AGC) computer that automatically makes minute adjustments in a generator's output to maintain a balance between the load and the available generation. These are fast fluctuations in the load that cannot be predicted or scheduled in advance and must be compensated automatically with sufficient generation resources online and available.

In the unit commitment time frame, a utility is concerned with the accuracy of the wind forecast for any wind generation on the system. Uncertainty in the wind forecast causes a system operator to perhaps schedule more of other types of generation than is actually needed in case the wind forecast is incorrect. In the load following time frame, the operator must have confidence in the availability of the wind resource for the next hour, and he must have adequate reserve capacity that can either be ramped up or down to compensate for any random fluctuations in the wind resource . In the regulation time frame, the wind resource is another level of uncertainty because if there is a temporary lull in the wind, the AGC will have to compensate with other generation resources.

The unit commitment time frame has the greatest uncertainty and therefore is considered the costliest to the utility. To put the impact of wind generation in perspective, look at the following table.

Table 4
Impact of Wind Generation On Ancillary Services (mills/kWh)

Requirement	Penetration	
	5%	20%
Regulation	0.0	1.5
Load Following	0.8	3.0
Unit Commitment	2.0	2.0
Total	3.0	6.0

As you can see from the table, at low wind penetrations there may be no impact on the regulation requirement and maybe 1 mill/kWh at higher penetrations. Unit commitment costs are fairly constant at about 2.0 mills/kwh and load following costs increase as the penetration level increases. There are numerous studies of the cost of wind energy on utility operations and the values presented here are just representative of some of the studies. Some studies show that there is a cost for regulation even at low penetrations and some of the studies indicate that the load following costs may be relatively flat regardless of the penetration level.

Utilities tend to consider the capacity value of wind energy to be between 10% and 30% of the nameplate capacity of the wind turbine.

Another issue for electric utilities is the ability of the wind turbine to remain operational through temporary fault conditions. One such condition is known as *low-voltage ride through* (LVRT) capability. The LVRT standard, which is FERC order 661-A, requires wind farms to remain in service during transmission faults of certain magnitudes. The standard requires wind farms to remain in service during three phase faults that bring the system voltage to zero for as long as 150ms without disconnecting from the system. The chart in Figure 12 shows the operating characteristics that the wind farm must be capable of operating within.

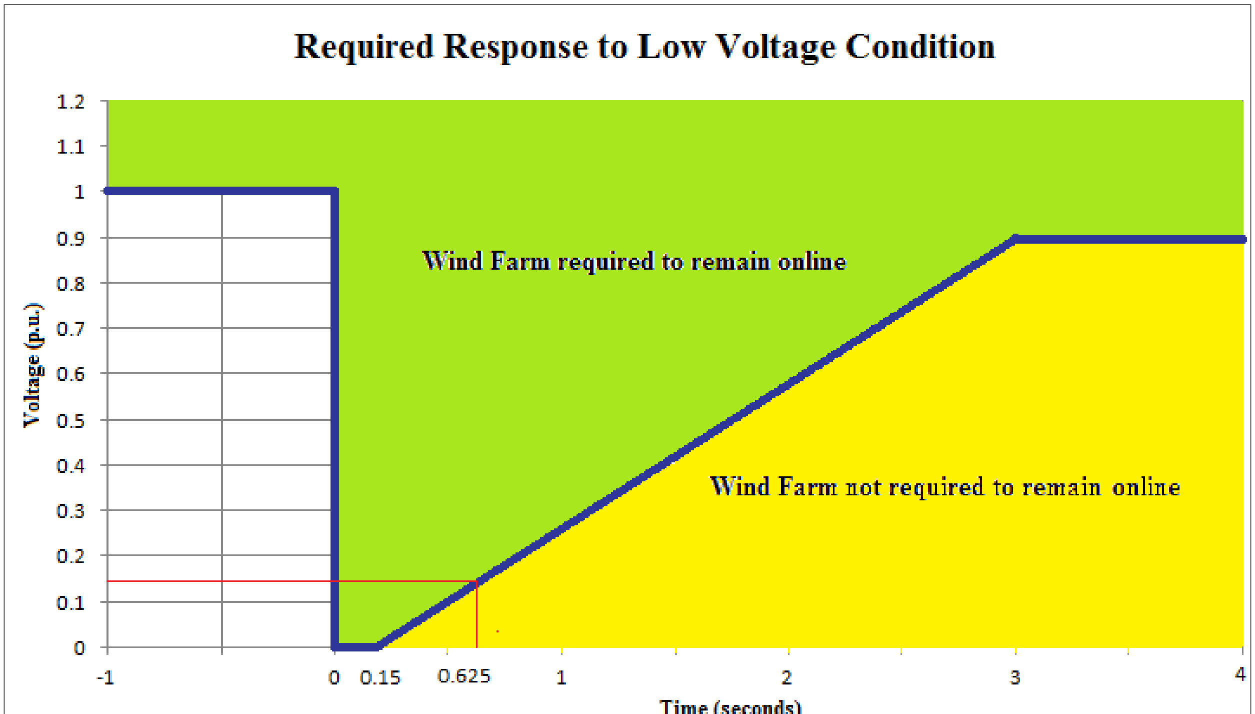


Figure 12

Looking at the chart in Figure 12, a wind farm must remain connected to the electric system even if the system voltage drops to zero for a period of up to 150ms. For a fault of 2-seconds or less, the wind farm must remain connected for system voltages as low as 0.60 per unit. For fault durations of 3-seconds or more, the wind farm must only remain connected for system voltages down to 0.90 per unit. Earlier wind farms (prior to 2008) only have to remain connected for voltages down to 0.15 per unit for fault durations of less than 625ms.

One caveat, utilities may require stricter requirements if necessary for the reliability of the electric power grid.

Environmental Impacts

From an environmental perspective, issues such as aesthetics, noise, bird mortality, and ice throw are common concerns when siting a wind farm.

Visual Impacts

The height of a wind turbine can raise concerns about the visual intrusion that a wind farm will have on an area. The height of a commercial wind turbine can easily exceed 300 feet including the rotor blades. A commercial wind farm of 50 MW will probably require 30-40 wind turbines spread across hundreds of acres, so the visual impact of a wind farm can be significant. In rural agricultural areas and other sparsely populated areas, wind farms have often been installed with little or no opposition from local residents. However, many of the good wind sites are in the mountains and other scenic areas and attempting to build a wind farm in these locations can result in significant opposition. Some areas, North Carolina in particular, have passed ridge laws to prevent the construction of tall structures the mountain tops.

Photo Credit: DOE/NREL

The land area for a wind farm can be significant. On average, a wind farm will require about 25 acres per megawatt of installed capacity. Therefore, a 50 MW wind farm will require approximately 1,250 acres. Of course, most of the land required is for separation of the wind turbines, and the land can still be used for farming and other uses.

The image on the right shows a wind turbine in the view shed of a residential neighborhood. This is the type of image many homeowners have when they hear that a wind farm may be sited near their property.

Noise Impacts

Noise is sometimes listed as a negative impact of a wind farm. However, the wind itself is likely to generate much more noise than the wind turbine. A typical wind ordinance requires that the noise from a wind turbine be less than 55 dBa at some distance from the wind turbine. At 800 feet, a modern large commercial wind turbine will generate approximately 45 dBa of noise. Some ordinances require a wind turbine to be set back at least 1,200 feet from the nearest occupied structure. Sound levels drop off dramatically with distance, so at any reasonable distance, the noise of a wind farm is probably not significant.

Bird Mortality

Migrating birds have been known to collide with wind turbine blades and there is a concern that the improper placement of a wind farm may lead to more bird deaths. As with any tall structure, wind turbines do create a risk for birds, but the impact is believed to be on par with other man-made structures. A greater than normal risk does occur though when wind turbines are installed in the migratory paths of birds. However, recent research says that birds rapidly adapt to the invasion of wind turbines and long-term effects may be minimal.

Ice throw

During periods of freezing rain, the rotor blades of a wind turbine will accumulate ice that ultimately will shed and drop off the blades. If the ice shedding occurs during the operation of the wind turbine, the ice may be thrown a significant distance. Some proponents of wind turbines claim that ice buildup on the blades will cause an unbalance on the blades, which will cause the turbine to automatically shut down until the ice melts. However, based on the experience of airplanes flying through ice, the ice on the blades may build up symmetrically, so that each blade receives about the same amount of ice and does not create an unbalance. The following formula has been suggested as a reasonable approximation of the ice throw potential of a wind turbine.

Ice Throw = 1.5 * (Hub Height + Rotor Diameter)

Where,
Ice Throw = distance, feet.
Hub Height = Height to the rotor hub, feet.
Rotor Diameter = Diameter of the rotor blade arc, feet.

Example. What is the potential ice throw from a wind turbine that is mounted on a 230 tower and has a rotor diameter of 130 feet?

Ice Throw = 1.5 * (230 + 130)
Ice Throw = 540 feet.

The preceding equation is only an estimate. Many factors including rotational speed, elevation of the turbine relative to surrounding terrain, and wind turbine geometry can affect the potential ice throw.

The concern about ice throw can be minimized by using instruments to monitor rotor imbalance and sensors to detect the presence of ice. However, neither of these measures has proven especially reliable at predicting the presence of ice.

Summary

Even with the concerns of grid interconnection and electric power system operation, the utility industry is working to find ways to integrate wind energy into electric system operations. The environmental concerns with wind energy can be overcome with careful site selection.
To help the United States meet its energy goals, wind energy must be considered as a viable component of a renewable generation portfolio. It is the lowest cost alternative for renewable power and there are many sites within the United States where the wind is sufficient to support large scale wind projects.

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