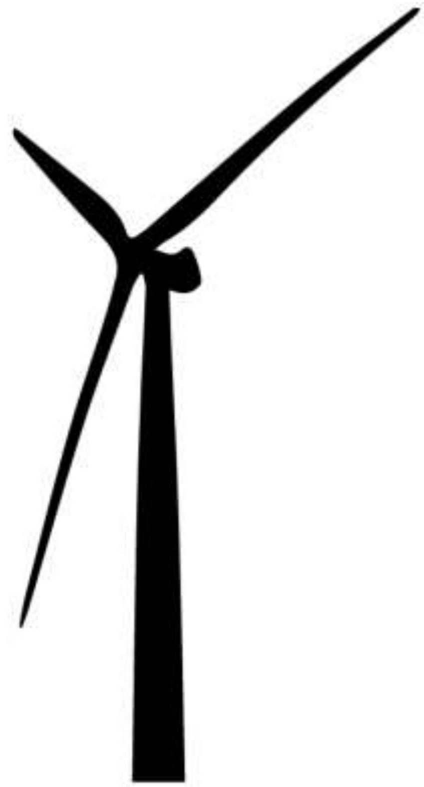
Generating Power from Wind

Introduction

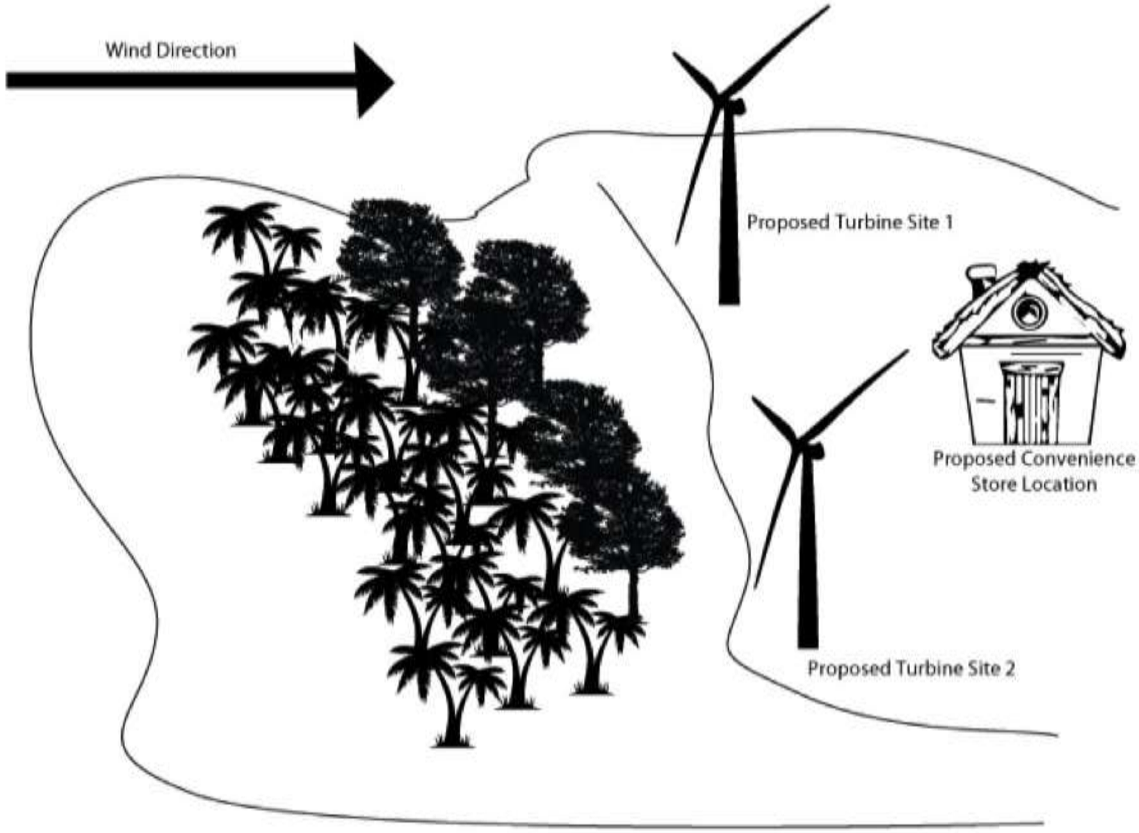


Wind can be defined as a natural movement of air at any velocity. Along the earth's surface, wind typically occurs "blowing horizontally" across the surface. It is renewable energy source that has a long history of use by humans. It has been used for thousands of years in many applications, including pumping water, grinding foods, and for sailing ships to explore new worlds.

"Wind power" is the conversion of wind energy into a useful form of energy. Today, wind energy is used for recreational purposes (e.g., sailing) as well as electrical power generation. Since wind is a clean "free" renewable resource, there has been an increase in the development of on-shore and off-shore wind farms across the U.S., as well as the world. In the U.S., the Department of Energy (2008) proposed that "Wind Energy Provides 20% of U.S. Electricity Needs by 2030."

You have been hired by Dolphin Cruise Lines to help with the implementation of a new wind turbine on the cruise company's private island. Several cruise ships visit this island each week and stop for tourists to explore, play, snorkel, relax, etc. Dolphin Cruise Lines would like to build a small convenience store on the island for tourists to help meet their personal needs (e.g., sunscreen, beverages, etc.).

In keeping with the island theme, Dolphin Cruise Lines has decided to construct the convenience store out of bamboo. In order to power the small convenience store Dolphin Cruise lines has hired you to explore the possibilities of constructing a small wind turbine to power the convenience store through wind power. One of the first things they need to know is how much power will be available from the proposed turbine (see picture & table).



Wind Turbines

A wind turbine is a device that converts kinetic energy from the wind into electrical power. They operate on a simple principle: as energy from the wind turns the blades around a rotor. The rotor is connected to the main shaft, which spins a generator to create electricity. Wind turbines are mounted on a tower to capture the most energy. At 100 feet (30 meters) or more above ground, they can take advantage of faster and less turbulent wind.

Wind turbines can be small or large in size. Small turbines are designed to directly supply a home or other building. Their variable output is balanced by battery storage and supplemented by the electrical grid or an on-site backup generator. Large turbines, like those found in wind farms, are designed to supply power to the electrical grid itself. The variable output of large wind turbines adds to the complexity of balancing supply and demand, because there is no large-scale storage on the grid.

Engineers design a variety of wind turbines that can rotate about either on a horizontal or a vertical axis. For this scenario, we will focus on design considerations for the widely used large “horizontal-axis wind turbine” (HAWT) found in wind farms.

The basic operation of most HAWTs requires them to be pointed into the wind. On small turbines, simple wind vanes help position them while large turbines used in wind farms use computer-controlled motors. The HAWTs turbines used in wind farms for commercial production of electric power are usually made with two or three blades and the blades are made stiff enough to prevent them from being pushed into the tower by high winds.

Blade design and engineering is one of the most complicated and important aspects of wind turbine technology. A blade acts much like an airplane wing. When the wind blows, a pocket of low-pressure air forms on the downwind side of the blade. The low-pressure air pocket then pulls the blade toward it, causing the rotor to turn. This is called lift. The force of the lift is actually much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a propeller, and the turning shaft spins a generator to make electricity. Today engineers are trying to design blades that extract as much energy from the wind as possible throughout a range of wind speeds

Turbines used in wind farms have high tip speeds of over 320 km/h (200 mph), high efficiency, and low torque ripple, which contribute to good reliability. The blades are usually colored white for daytime visibility by aircraft and range in length from 20 to 40 meters (66 to 131 ft) or more.

The tubular steel towers range from 60 to 90 meters (200 to 300 ft) tall. The blades rotate at 10 to 22 revolutions per minute. At 22 rotations per minute the tip speed exceeds 90 meters per second (300 ft/s). A gear box is commonly used for stepping up the speed of the generator, although designs may also use direct drive of an annular generator. Some models operate at constant speed, but more energy can be collected by variable-speed turbines which use a solid-state power converter to interface to the transmission system. All turbines are equipped with protective features to avoid damage at high wind speeds, such as feathering the blades into the wind (helps stop the rotation) or supplemental brakes for slowing them down.

Wind turbines output power that is measured in watts. Manufacturers measure the maximum, or rated, capacity of their wind turbines to produce electric power in megawatts (MW) with one MW is equivalent to one million watts. The production of power over time is measured in megawatt-hours (MWh) or kilowatt-hours (kWh) of energy. A kilowatt is one thousand watts. Production of power at the rate of 1 MW for 1 hour equals 1 MWh of energy.

Wind turbines vary in their power capacity. Popular early models of turbines generated 1.5-megawatts. Today's modern turbines generate power in the range of 2-3 megawatts.

Every wind turbine has a range of wind speeds, typically around 30 to 55 mph, in which it will produce at its rated, or maximum, capacity. At slower wind speeds, the production falls off dramatically. If the wind speed decreases by half, power production decreases by a factor of eight. On average, therefore, wind turbines do not generate near their capacity. Industry estimates project an annual output of 30-40%, but real-world experience shows that annual outputs of 15-30% of capacity are more typical. Wind turbines produce at or above their average rate around 40% of the time. Conversely, they produce little or no power around 60% of the time.

Wind Engineering

Wind engineering analyzes the effects of wind in the natural and in the human-built environment. It also studies the possible damage, inconvenience, or benefits which may result from wind. In the field of structural engineering, it includes strong winds, which may cause discomfort, as well as extreme winds, such as in a tornado, hurricane or heavy storm, which may cause widespread destruction. Before beginning with designing and building wind turbines, engineers need to have a good understanding of how wind loads impact structures.

Wind Loads on Structures

Wind engineers are often involved in the design, installations, and operation of wind turbines. In their studies, they learn how to analyze the effects of wind in natural and built environments and learn how to calculate wind loads on structures.

High winds can be very destructive. The speed of the wind (or wind velocity) acts as pressure when it meets with a structure. The intensity of that pressure is called the wind load. Calculating wind load is necessary for the design and construction of safer, more wind-resistant structures.

Design of Wind Farms

In the design and development of wind farms, engineers must consider many items, including the hardware to be used, the best sites to place the wind turbines, how to tie into the power grid, and how to address environmental concerns (e.g., such as noise). They are also involved in predicting and maximizing the power that can be obtained from the wind turbines.

After engineers have a good understanding of wind loads, they can begin to design wind turbines that are used in wind farms. Wind turbines used in wind farms must be as safe and efficient as possible. In designing wind farms, engineers must take into account many factors, including those related to:

- Geographic Location
- Wind Power
- Efficiency
- Power Output

Geographic Location

Engineers are often involved in appraising the energy available from the wind. The amount of energy available from the wind has several components. One component is wind velocity, measured either in meters per second (m/s) or miles per hour (mph). Another component is the distribution of the wind, in other words, how often the wind blows at a given velocity and direction and for how long the wind blows, or the duration of a given velocity. Air density also plays a role - lower elevations have thicker, denser air, and higher elevations have thinner, less dense air. If a wind turbine was put on the top of Mount Everest (8850m/29,035 ft) and the same kind of turbine on the beach near sea level, when both turbines experience a consistent 9 m/s (20 mph) wind, the turbine on the beach would produce more power because of the greater air density.

Wind Power

Wind turbines are used to convert the kinetic energy from the wind into mechanical power. A very important consideration when designing wind turbines is to determine how much power, measured in watts, a wind turbine can make. Determining the maximum wind power a turbine can generate depends on 3 main variables:

- The size of the turbine
- The speed of the wind
- The efficiency of the turbine and generator

Efficiency in Extracting Wind Power

When designing wind turbine, engineers know that it is physically impossible to extract all the energy from the wind and must consider efficiency in extracting wind power (P). The proportion of the power in the wind that the rotor can extract is often referred to as the “coefficient of performance,” “power coefficient,” or “efficiency” and is noted by “Cp.”

When considering a wind turbine project, engineers first use the wind power equation to find the maximum possible output in watts.

$$\text{Wind Power} = \tfrac{1}{2} * \rho * A * V^3$$

Next, engineers consider wind turbine efficiency and know there is a maximum value of Cp of 59.3%, meaning, even in ideal circumstances the best turbine cannot run at greater than 59.3% efficiency.

This principle, known as Betz Law, allows engineers to calculate the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow. According to Betz’s law, no turbine can capture more than 16/27 (59.3%) of the kinetic energy in wind. Therefore, the maximum turbine output (PT) is as follows.

$$\text{Wind Power (with Betz Law)} = \tfrac{1}{2} * \rho * A * V^3 * Cp$$

-where Cp = 16/27

In real-world applications however, engineers realize that turbines will get far less than 59.3% efficiency – 59.3% simply represents the maximum possible power that could be generated. Engineers consider typical losses due to inefficiencies from the turbine (C_t = 40%) and from the alternator (C_a = 60%) to get a good an idea of what to expect in power output (watts) at a particular wind speed. When engineers apply these to the *Wind Power Equation* the result is the *Turbine Power Equation.* The turbine power equation gives engineers a more accurate idea of what power output to expect from a wind turbine. Note: These numbers of turbine and alternator efficiency will vary depending on the designs and their specific performance curves

Tip Speed Ratio

The Tip Speed Ratio (*TSR*) is another important factor in wind turbine design. TSR refers to the ratio between the wind speed and the speed of the tips in the wind turbine blades. If the rotor of the wind turbine spins too slowly most of the wind will pass through the gaps in the blades. If the rotor spins too quickly the blades will blur and act like a solid wall to the wind. An additional factor to consider is turbulence; rotor blades create turbulence as they spin through the air. If the next blade arrives too quickly it will lose speed as it hits the turbulence caused by the previous blade.

Formulas

Description	Equation
Wind Load	F = A * Pr * Cd
Wind Power	P=½ * ρ * Ar * V³
Wind Power With Betz Law	PT = ½ * *ρ* * Ar * V³ * Cp where Cp = 16/27
Turbine Power Equation	P = ½ * *ρ* * Ar * V³ * C_t * C_a
Tip Speed Ratio	TSR = $\frac{\textit{Tip Speed of Blade}}{\textit{Wind Speed}}$ Where wind speed is measured in m/sec
Tip Speed of Blade	Tip Speed = $\frac{2\pi r}{T}$ T = time (seconds) for one revolution
Optimum Tip Speed Ratio	TSR (Max Power) = $\frac{4\pi}{n \text{ (number of blades)}}$

Variables

F = force (lbs)

A = Area

*Rectangle = l * w*

Surface of a Cylinder = 2*πrh*

C = circumference

Circumference of a circle = 2*πr*

Pr = Pressure

P (pounds per square foot) = .00256 * V^2

Where *V* is measured in ft/sec

V = wind speed (meters/sec)

Cd = Drag coefficient

Cd = 2.05 for cubes

Cd = 1.17 for cylinders

P = power in watts

ρ = The air density (1.23 kg/m³ @ sea level and 20° C)

Ar = The swept area of the turbine blades

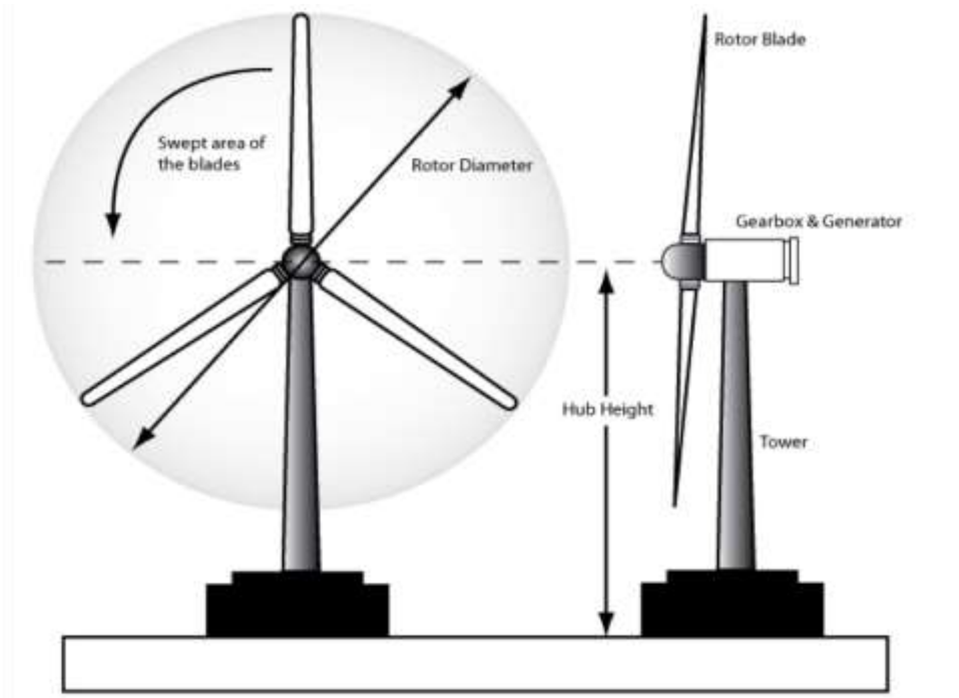
Ar = π * r^2

V = wind speed (meters per second)

C_t = Percentage loss form Turbine

C_a = Percentage loss from Alternator

Basic Turbine Layout



Questions 41-42

Turbine & Location Details

Blade length, l = 22 meters
Number of blades = 3
Average Island Wind speed, v = 10 m/sec
Air Density, ρ = 1.23 kg/m^3
C_t = 40% (Turbine efficiency rating)
C_a = 65% (Alternator/Generator efficiency rating)

41. Using the provided conditions, determine the *maximum* possible power (in megawatts), taking into account Betz Law, that could be produced by the wind turbine proposed to power the convenience store.

a. .025 MW

b. .55 *MW*

c. .93 *MW*

d. 5.54 *MW*

e. 9.35 *MW*

42. Determine a realistic (taking into account mechanical inefficiencies) power output (in megawatts) for your client that could be produced by the wind turbine.

a. .24 *MW*

b. .37 *MW*

c. .40 *MW*

d. 2.43 *MW*

e. 4.01 *MW*

Work it Out

Question 43-44

An important concept in the construction of any building (e.g., the small convenience store) is wind load (the force enacted on the building by the wind). Wind engineers who install wind turbines are also involved in calculating wind load. Dolphin Cruise Lines is interested in the "wind load" on the small convenience store and the tower holding up the wind turbine.

43. Calculate the wind load on the wind-facing wall of the building using the following details: The convenience store wind-facing wall dimensions are: 12' tall, 20' long. How much force (in lbs) will be exerted on the wind-facing wall of the building by the wind?

   a. 125.95 lbs
   b. 773.76 lbs
   c. 1259.52 lbs
   d. 1355.87 lbs
   e. 492000 lbs

44. Calculate the wind load on the turbine tower using the following details: The tower for the turbine has a radius of 48 inches and a height of 260 feet (assume a uniform cylindrical shape for the tower). How much force (in lbs) will be exerted on the tower by the wind?

   a. 9793.73 lbs
   b. 11749.71 lbs
   c. 19572.24 lbs
   d. 21067.31 lbs
   e. 252807.75 lbs

Work it Out

Questions 45-47

Turbine & Location Details
Blade length, *l* = 22 meters
Average Island Wind speed, *v* = 10 m/sec
Air Density, ρ = 1.23 kg/m^3
C_t = 40% (Turbine efficiency rating)
C_a = 65% (Alternator/Generator efficiency rating)
T (time it takes each rotor to make one revolution) = 1.1582 sec

45. Calculate the distance traveled (in feet) by the tip of each blade in one revolution and the revolutions per *minute* of the proposed turbine.

    a. 138.23 m., .8634 rpm

    b. 138.23 ft., 66.47 rpm

    c. 326.73 ft., 59.63 rpm

    d. 453.51 ft., 51.80 rpm

    e. 453.51 ft., 69.42 rpm

46. Calculate the Tip Speed Ratio for the proposed turbine.

    a. 8.96

    b. 10.30

    c. 11.93

    d. 13.82

    e. 16.01

47. Calculate the difference between the optimum Tip Speed Ratio (for maximum power output) and the Tip Speed Ratio for the proposed turbine (as found in problem 46).

    a. 4.77

    b. 7.74

    c. 8.54

    d. 9.63

    e. 9.76

Work it Out

Question 48

Suppose you research wind turbines on an island in close proximity and discover that the average wind speed on nearby islands is 13 m/sec and the average TSR is 4.3.

48. In this scenario, assume a 3-blade turbine is being used and it takes 1.593 seconds for each blade to make one revolution. What length of blades (in feet) should be purchased for the proposed Dolphin Cruise Lines' turbine in order for it match the TSR obtained on the other islands?

    a. 14.17 ft.

    b. 44.73 ft.

    c. 46.49 ft.

    d. 55.91 ft.

    e. 89.05 ft.

Work it Out

Question 49-50

Some of the engineers on the team have proposed choosing a different site for the wind turbine (see scenario picture). The turbine and blade dimensions would be the same, but the site and wind speed would be different.

SITE 1: Turbine & Location Details

Blade length, *l* = 22 meters
Number of blades = 3
Average Island Wind speed, *v* = 10 m/sec
Air Density, ρ = 1.23 kg/m^3
C_t = 40% (Turbine efficiency rating)
C_a = 65% (Alternator/Generator efficiency rating)
T (time it takes each rotor to make one revolution) = 1.1582 sec

SITE 2: Turbine & Location Details

Blade length, *l* = 22 meters
Number of blades = 3
Average Island Wind speed, *v* = 12 m/sec
Air Density, ρ = 1.23 kg/m^3
C_t = 40% (Turbine efficiency rating)
C_a = 65% (Alternator/Generator efficiency rating)
T (time it takes each rotor to make one revolution) = .976 sec

49. Which site should your team choose to maximize power output and efficiency (select the site that provides the TSR *closest* to the ideal TSR)? What is the calculated TSR for the site you selected?

   a. Site 1, 7.96
   b. Site 1, 11.93
   c. Site 2, 4.19
   d. Site 2, 7.61
   e. Site 2, 11.80

50. If site 2 were chosen what would the calculated wind load be for the proposed turbine in site 2? The tower for the turbine would have the same specifications as the tower outlined for site1.

   a. 1366.4 lbs
   b. 19794.5 lbs
   c. 20041.9 lbs
   d. 30336.9 lbs
   e. 53154.5 lbs

Work it Out