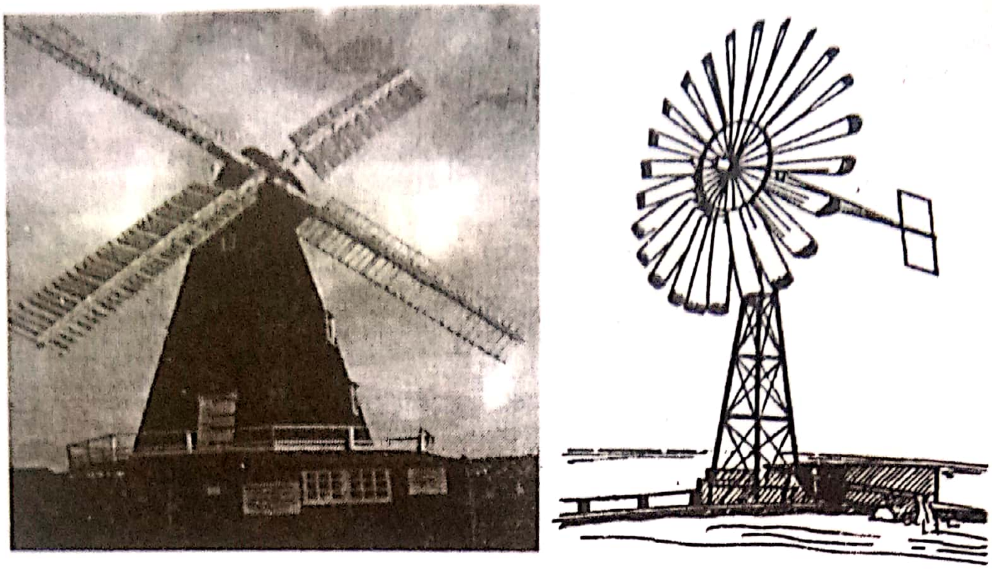
16

Electric Power from Wind Energy

16.1. Overview

Wind is a source of free energy. The use of sails on ships moves them through the oceans and seas by the action of winds. The famous 'trade winds' sets the exchange of trade between continents through vessels aided by directional winds. The wind has been used for pumping water for many centuries for irrigation and domestic purposes, for grinding flour and pumping water; it was in fact the primary method used for dewatering large areas of the Netherlands from the thirteenth century onwards. The technology of high power, geared transmissions was developed centuries ago by windmill [see figure 16.1(a)] designers and the fantail wheel [see figure 16.1(b)] for keeping the main sales pointing into the wind was one of the world's first examples of an automatic control system. The rotation of the flaps due to wind flow is transmitted by a mechanism, which drives the required machinery for a particular purpose.



(a) (b)

Figure 16.1: (a) A Wind Mill (b) Fantail Wheel

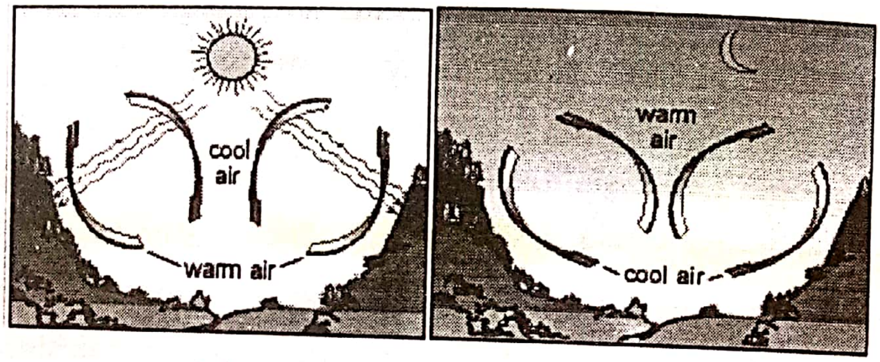
It is a well-known fact that wind energy has been in existence for a long time; however, it is not treated as a main source for obtaining benefits for most commercial and home uses. This is because of the reason that coal and natural gas is considered to be the main energy sources; however, they are available for limited period of time and must therefore be saved for our next generation to come. Because of the limited amount of coal, natural gas and oil and the rise in their prices, it is important to find out alternatives so that the industrial, commercial and residential requirements can be fulfilled. These energy sources have no negative effects on the environment and this is one of the main reasons why its usage has been encouraged. Sun, wind and water are all considered to be the renewable sources of energy. It is a well-known fact that solar panels have taken a significant role in energy sector. On the other hand, wind energy is available in abundance and large amount of benefits can be obtained. The use of wind energy in the generation of electricity must be promoted so that energy at cheaper rates may become available.

Wind power generation depends on the kinetic energy of wind and wind turbine is the equipment that converts this kinetic energy in the wind into mechanical energy. When this mechanical energy is applied to a pump, it lifts water; applied to a grinder, it grinds the wheat to form flour. When coupled to an electricity generator, the mechanical energy is converted to electricity. Though modern technology has made dramatic improvements to the efficiency of windmills, they are still dependent on the vagaries of the weather. Not just on the wind direction but on the intermittent and unpredictable force of the wind.

16.2. Wind Geography and Site Selection

The wind is a by-product of solar energy. Approximately 2% of the sun's energy reaching the earth is converted into wind energy. The surface of the earth heats and cools unevenly, creating pressure zones in the atmosphere that make air flow from high to low-pressure areas. Wind direction is also variable; the strongest winds generally prevail out of the southwest to northwest. Knowledge of the prevailing wind direction is important for locating the wind turbine in the least obstructed setting possible. If the entire earth surface consisted of flat and smooth land, there would be little wind variation from place to place. But with the addition of hills, valleys, river bluffs, lakes, trees and sky-rise buildings, a complex and highly variable wind regime is created. Trees and buildings, however, add to the complexity of the wind on a smaller scale. Each geographical feature influences wind flow in certain patterns. Hills, plateaus and bluffs provide high ground on which to locate a wind turbine into a region of higher 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.

The mechanism of wind flow can be understood as follows: When the sun shines in the morning, it heats up the land and warm air rises by natural convection and replaced by cool air due to temperature gradient. 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. During the nighttime, the land cools by giving away its heat, which moves upward, replaced with cooler air. This process keeps the air in motion in the form of wind. Valleys often experience calm conditions at night even when adjacent hilltops are windy. This is illustrated in figure 16.2 (a) and 16.2 (b) respectively.



(a) (b)

Figure 16.2: Movement of Air in Valleys (a) Day Time (b) Night Time

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 ridgeline. 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.

Land areas adjacent to large bodies of water may be good wind sites for two reasons. First, a 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 'on-shore'. 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. Since land heats more quickly than water, the cooler air from over the water replaces the warm rising air over the land. This produces an on-shore breeze of typically 8-12 mph or more. At night the breeze stops or reverses direction, as the land cools more quickly. This situation is illustrated in figure 16.3.

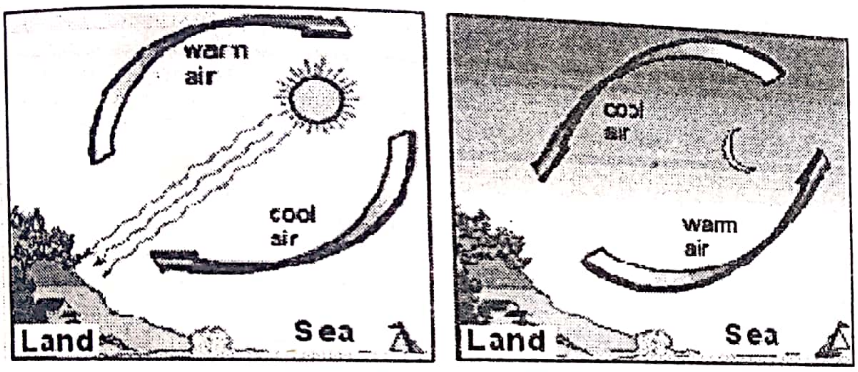


Figure 16.3: Land and Sea Breeze

16.3. Nature of Surface and Obstacles

The wind speed is generally affected by the surface over which the wind blows. Obstacles, such as areas with trees and buildings, will produce more friction and turbulence than smooth surfaces such as lakes or open cropland. The greater friction offered by obstacles thus reduces the wind speed near the ground. Consider a thin layer of wind blowing along the ground. Air molecules are being dragged along the ground, into trees, bushes, buildings, etc. This slows those molecules down. The next layer up drags against these slow molecules, and slows down a little bit less and so on. This effect is related to the air density, wind velocity, and air viscosity. This is referred in aerodynamics as a boundary layer. The wind is thus slower at the ground. Trees, plateaus and buildings are the most common obstacles to wind. They act to disturb the air both upwind and downwind of the obstruction by reducing wind speed and increasing turbulence as illustrated in figure 16.4.

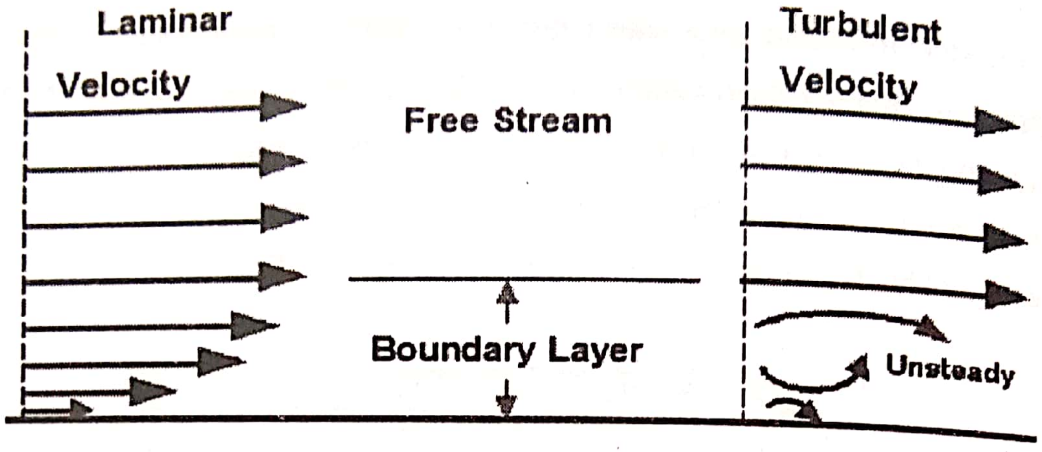


Figure 16.4: Wind Flow Illustration over Terrain (Source: Glenn Research Laboratories, NASA)

The flow of winds over buildings and other such obstacles will divide and distort the streamlines, forming eddies, thus giving rise to turbulence as illustrated in figure 16.5. Buildings that are wider than they are tall have an influence on air flow at greater distances downwind than do taller buildings and the wind power is affected. For example, at a distance 20 times the building height downwind, only very wide buildings produce more than a 10% decrease in the available wind power for those in which width divided by height equal to or greater than 3. On the other hand, tall, narrow buildings will create power reductions of less than 10% at distances as close as 5 building heights downwind. It must be remembered that most residential structures, such as houses, barns and garages, are wider than they are tall.

The approximate increase of speed with height for different surfaces can be calculated from the following equation:

$$V_2 = V_1\left(\frac{h_2}{h_1}\right)^n \qquad 16.1$$

Where V_1 is the known (reference) wind speed at height h_1 above ground, V_2 is the speed at a second height h_2, and n is the exponent determining the wind change. Values for n are listed in table 16.1 for different types of ground surface cover. If the wind comes across a fallow crop field, you do not have to reach as high for greater wind speeds as you would in a forest or suburb.

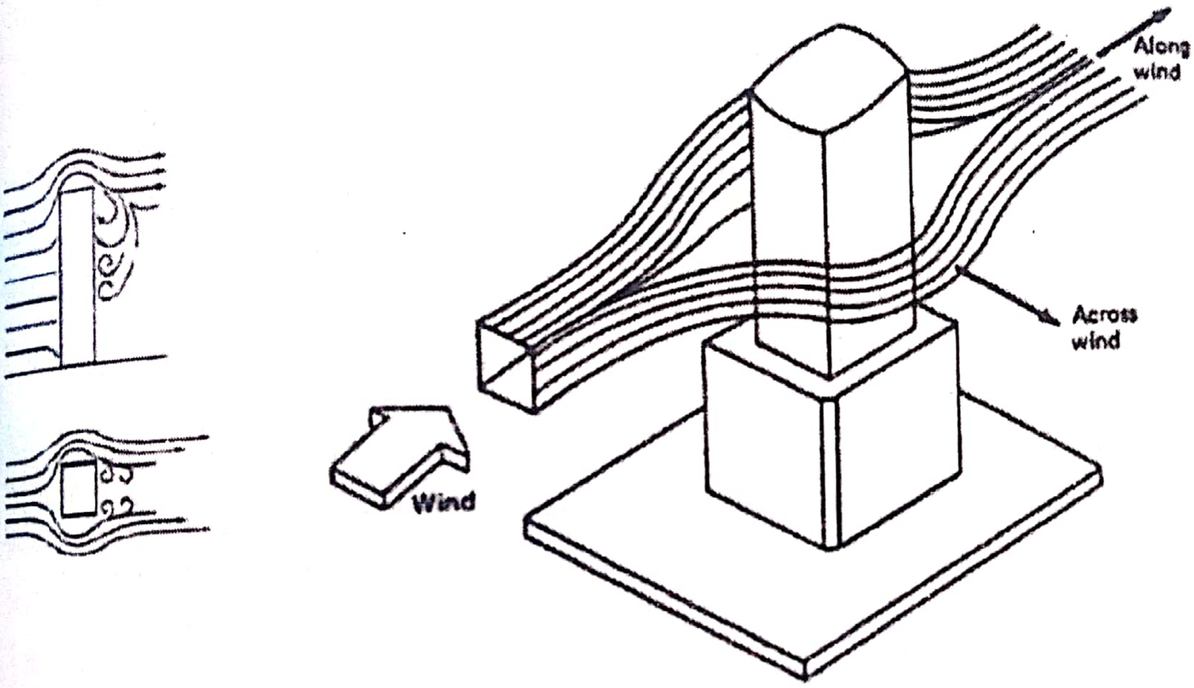


Figure 16.5: Wind Flow Illustration across Obstacles

Table 16.1: Variation of n with Ground Surface

Ground Surface Cover	*n*
Smooth surface, ocean and sand	0.10
Low grass or fallow ground	0.16
High grass or low crops	0.18
Tall row crops or low woods	0.20
High woods with trees and small tows	0.30

This method, however, only provides a rough estimate of wind speeds. It is most useful when using average and not instantaneous wind speeds. In addition, equation 16.1 should only be used for relatively flat terrain because hills and mountains often have unpredictable influences on wind characteristics. Lastly, within dense vegetation, such as a forest or an orchard, a new effective ground level is established at approximately the height where the branches of adjacent trees touch. Below this level there is little wind. In a dense cornfield, this height would be the average corn height. In a forest, it would be the average height of the tree canopy, and so on. When using the wind speed equation all heights should be expressed above the effective ground level.

Example 16.1: An anemometer* placed on a rooftop of a building, 30 feet high registers an average wind speed of 10mph. It is desired that a wind turbine is to be located on a tower of height 100 feet from the ground. Assuming value of n to be equal to 0.2, find the wind speed that may be encountered by the wind turbine.

Given that:

V_1 = 10mph

h_1 = 30 feet

h_2 = 100 feet

n = 0.2

Using: $V_2 = V_1\left(\frac{h_2}{h_1}\right)^n = 10\times\left(\frac{100}{30}\right)^{0.2}$ = **12.72 mph**

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* An instrument used for measuring wind speed (see section 16.6).

16.4. Wind Speed and Shear

The rate of flow of wind is known as the wind speed. The wind blows faster at higher altitudes because of the viscosity of air and the drag from the land and sea. The variation in velocity with altitude, called wind shear, is most effective near the surface. Wind shear refers to a change in wind speed or direction with height in the atmosphere. Wind shear can also refer to a rapid change in winds over a short horizontal distance experienced by aircraft, conditions that can cause a rapid change in lift, and thus the altitude of the aircraft. In general, wind shear refers to any change in wind speed or direction along a straight line. In the case of hurricanes, wind shear is important primarily in the vertical direction from the surface to the top of the troposphere. Wind shear is often the most critical factor controlling the formation of tornadoes. Wind shear in an atmospheric layer that is clear, but unstable, can result in clear air turbulence. A general rule of thumb is that the shear must be 20 knots or less (1 knot or nautical mile = 0.514 m/s) for intensification to occur. Most instances of rapid intensification of hurricanes occur when the wind shear is 10 knots or less. The wind shear formula from the Danish Wind Industry Association is:

$$V = V_{ref} \frac{\log_{10}(z/z_0)}{\log_{10}(z_{ref}/z_0)} \qquad 16.2$$

Where z_0 is a parameter called the roughness length for a particular roughness class. The roughness classes are defined for roughness length in meter (z_0), which results to the height above ground level where the wind speed is theoretical zero. The roughness length for typical countryside (agricultural land with some houses and sheltering hedgerows with some 500 meters intervals; 'roughness class 2') is $z_0 =$ 0.1m. Table 16.2 lists the roughness length and roughness class for different terrains. V_{ref} is the speed at a reference height z_{ref} such as 10 meters and V is the wind speed at a height z.

Average wind speeds usually tend to increase with height and then levels off. This is the reason why wind turbines are usually installed as high above ground as possible. An empirical formula developed by D.L. Elliott of Pacific Northwest Labs gives the wind speed V at a height h above ground level as:

$$V = V_{ref} \left(\frac{h}{h_{ref}} \right)^m \qquad 16.3$$

Where V_{ref} is the reference wind speed at a reference height $href$ and the exponent m is a correction factor dependent on obstacles on the ground, the density of the air and wind stability factors. Typically, during the day the variation follows the 1/7th power law, which concludes that wind speed rises proportionally to the seventh root of altitude. In wind resource assessments m is commonly assumed to be a constant 1/7 or 0.143, so that equation 16.3 can be written as:

$$V = V_{ref}\left(\frac{h}{h_{ref}}\right)^{\frac{1}{7}}. \qquad 16.4$$

Table 16.2: Roughness Class and Roughness Length

Roughness Class	Roughness Length, z₀ in m	Energy Index (%)	Land Scape
0	0.0002	100	Water surface
0.5	0.0024	73	Open terrain with smooth surface i.e. runways
1	0.03	52	Agricultural area, no fences or hedges, scattered buildings,
1.5	0.055	45	Agricultural area, some houses, hedges with min. 1250m or ¾ mile distance
2	0.1	39	Agricultural area, couple of houses, hedges with min. 500m or ¼ mile distance
2.5	0.2	31	Agricultural area with houses, shrubs, trees and hedges with min. 250m distance
3	0.4	24	Villages, small towns forests or very rough and uneven terain
3.5	0.8	18	Lager cities with tall buildings
4	1.6	13	Very large cities with tall buildings

The wind power is dependent on wind speeds. Doubling the height of the tower increases the wind speed by 10% and the expected power by 34%. Increasing tower height five times increases the wind speed by about 25% and almost doubles the power available. Figure 16.6 shows the relationship between wind power and height above the ground.

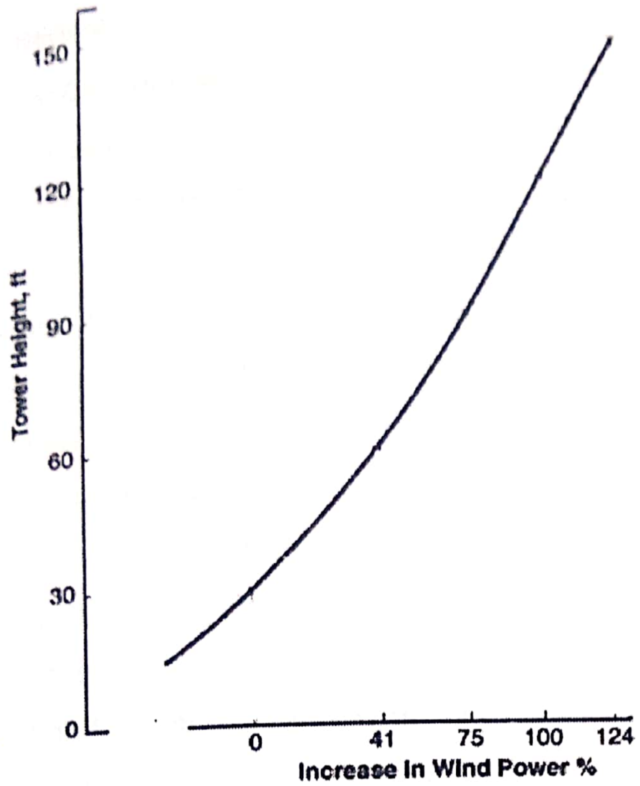


Figure 16.6: Wind Power Variation with Height

It has been recommended that towers should be at least 24-37 meters (80-120 feet) high. Installing a wind turbine on a tower that is too short is like installing a solar panel in a shady area. At a minimum, mount a wind turbine high enough on a tower that the tips of the rotor blades remain at least 9 meters (30 feet) above any obstacle within 90 meters (300 feet).

Though the force and power of the wind are difficult to quantify, various scales and descriptions have been used to characterize its intensity. The Beaufort scale is one measure that is used commonly. The Beaufort scale, (named after admiral in the British navy, Sir Francis Beaufort) was devised in 1805 as a means of describing the effect of different wind velocities on ships at sea. According to this scale the force of the wind, ranging from 0 (calm) to 12 (hurricane) is classified. A wind classified as 0 has a velocity of less than 1.6 km (1 mi) per hour; a wind classified as 12 has a velocity of over 119 km (74 mi) per hour. Thus the lowest point or zero on the Beaufort scale corresponds to the calmest conditions when the wind speed is zero and smoke rises vertically. The highest point is defined as force 12 when the wind speed is greater than 34 meters per second or 75 mph as occurs in tropical cyclones when the countryside is devastated by hurricane conditions. Wind turbines generally operate between force 3 and force 7 on the Beaufort scale with the rated capacity commonly being defined at force 6 with a wind speed of 12m/s (force 6 on the Beaufort scale corresponding to a strong breeze). Below force 3 the wind turbine will not generate significant power. At force 3, wind speeds range from 3.6–5.8 m/s or 8–13 mph. Wind conditions are described as 'light' and leaves are in movement and flags begin to extend. At force 7, wind speeds range from 14–17 m/s or 32–39 mph. Wind conditions are described as 'strong' and whole trees are in motion. With winds above force 7 the wind turbine should be shut down to prevent damage. In 1906, the descriptions were changed to how the sea behaved, instead of the sails, and also land observations were made. The Beaufort scale was extended in 1946, when forces 13–17 were added. However, forces 13–17 were intended to apply only to special cases, such as tropical cyclones. Nowadays, the extended scale is only used in Taiwan and Mainland China, which are often affected by typhoons. Wind speed on the 1946 Beaufort scale is defined by the empirical formula:

$$V = 0.836B^{3/2} \qquad 16.5$$

Where V is the equivalent wind speed in meters per second at 10 meters above the surface and B is Beaufort scale number. For example, B = 9.5 is related to 24.5 m/s which is equal to the lower limit of '10 Beaufort'. Different values of Beaufort scale for various wind conditions are given in Appendix I.

Example 16.2: Determine the wind speed in mph for a generally gale force wind over land.

From table shown in Appendix I, the gale force winds are rated as force 8 on a Beaufort scale, thus B = 8. Using:

$$V = 0.836B^{3/2}$$

$$V = 0.836(8)^{3/2} = 18.91 \text{ m/s}$$

$$V = \frac{18.91 \times 3600}{1000 \times 1.6} = \mathbf{42.54\ mph}$$

Or

Example 16.3: Calculate the wind speed at a height 100 meters in a region with geographical rough and uneven terrain and having small towns and forest graded as classified as roughness class 3. Assume a reference wind speed of 1mph at a reference height of 10 meters.

Given that:

$z = 100$ m

$z_{ref} = 10$ m

$V_{ref} = 1$ mph

From the data given in table 16.2, the region in question is roughness class 3 for which the roughness length is $z_0 = 0.4$. Therefore using:

$$V = V_{ref} \frac{\log_{10}(z / z_0)}{\log_{10}(z_{ref} / z_0)}$$

Or

$$V = 1 \times \frac{\log_{10}(100/0.4)}{\log_{10}(10/0.4)} = \mathbf{1.72\ mph}$$

Example 16.4: From the data given in example 16.3, calculate the wind speed when the wind speed at reference height corresponds to force 7 on the Beaufort scale.

Given that:

$B = 6$

From the table given in Appendix I, it corresponds to 22–27 knots, which can be converted to mph, or alternatively using:

$$V = 0.836B^{3/2}$$

$$V = 0.836(6)^{3/2} = 12.28 \text{ m/s}$$

Or

$$V = \frac{12.28 \times 3600}{1000 \times 1.6} = 27.63 \text{ mph}$$

This is taken as V_{ref} at a reference height of 10 meters. Therefore using:

$$V = V_{ref}\frac{\log_{10}(z/z_0)}{\log_{10}(z_{ref}/z_0)}$$

Or
$$V = 27.63\times\frac{\log_{10}(100/0.4)}{\log_{10}(10/0.4)} = \mathbf{47.4\ mph}$$

Thus a wind speed of 47.4 mph at a height of 100 meters, which is 21.2 m/s or 41.2 knots, which according to force 9 on Beaufort scale (strong gale conditions). Thus the difference in speed and wind conditions is vast at a height of 100 meters above the ground.

16.5. Wind Consistency

Wind power has the advantage that it is normally available 24 hours per day, unlike solar power, which is only available during daylight hours. Unfortunately the availability of wind energy is less predictable than solar energy. At least we know that the sun rises and sets every day. Nevertheless, based on data collected over many years, some predictions about the frequency of the wind at various speeds, if not the timing, are possible.

The simplest method of measuring mean wind speeds is to install an anemometer, which will be discussed in the next section. Ideally such instruments should be read three times per 24 hours, in the early morning, at mid-day and in the evening to allow the diurnal (day-night) pattern of wind to be recorded. This allows the mean wind speeds for the mornings, afternoons and night periods to be separated. Failing this, an early morning and an evening reading should be taken each day to allow day and night averages to be calculated. Daily or weekly readings provided they are consistently and accurately recorded, are better than nothing, although they will not show diurnal patterns.

A commonly used approach is to record the frequency with which the wind speed is measured to be blowing within a series of pre-defined speed referred to as 'bins', such as 0-5 km/h, 5-10 km/h, 10-15 km/h, and so on. If more accurate results are required, and then narrower bins may be defined to improve the resolution, however, this requires a more sophisticated analytical work. The most useful starting point for any sophisticated attempt to predict the performance of a wind system in a given wind regime is to create or obtain a velocity-frequency histogram which shows the percentage of the time that the wind blows at different speeds. A typical velocity-frequency histogram is shown in figure 16.7, which has been constructed from hourly wind data by adding up how many hours in the year, on average, the wind was recorded as having been blowing at a velocity within each pre-defined bin. For example, the bins are at 1 mph intervals, and there were about five-hourly records of zero mph, hundred-hourly records of 1 mph, and so on. It is also quite common to present wind data as a velocity-frequency curve. These are in effect fine resolution velocity-frequency histograms. The average wind speed over the regime and the maximum and minimum wind speed over a regime can be obtained from the curve. The wind regime of a given site is characterized by the velocity-frequency curve, which will have a similar shape every year and will not vary much over the years. Velocity-frequency curves can be synthesized by a sophisticated mathematical process using what is known as a Weibull Probability Distribution Function. The 2-parameter Weibull cumulative distribution function $F(t)$, has the explicit equation:

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \qquad 16.6$$

Where t is the time, cycles, miles, or any appropriate parameter, η is the characteristic life or scale parameter and β is the slope or shape parameter. The Weibull probability density function can then be expressed as:

$$F(t) = \beta\left(\frac{t^{(\beta-1)}}{\eta^{\beta}}\right)\exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \qquad 16.7$$

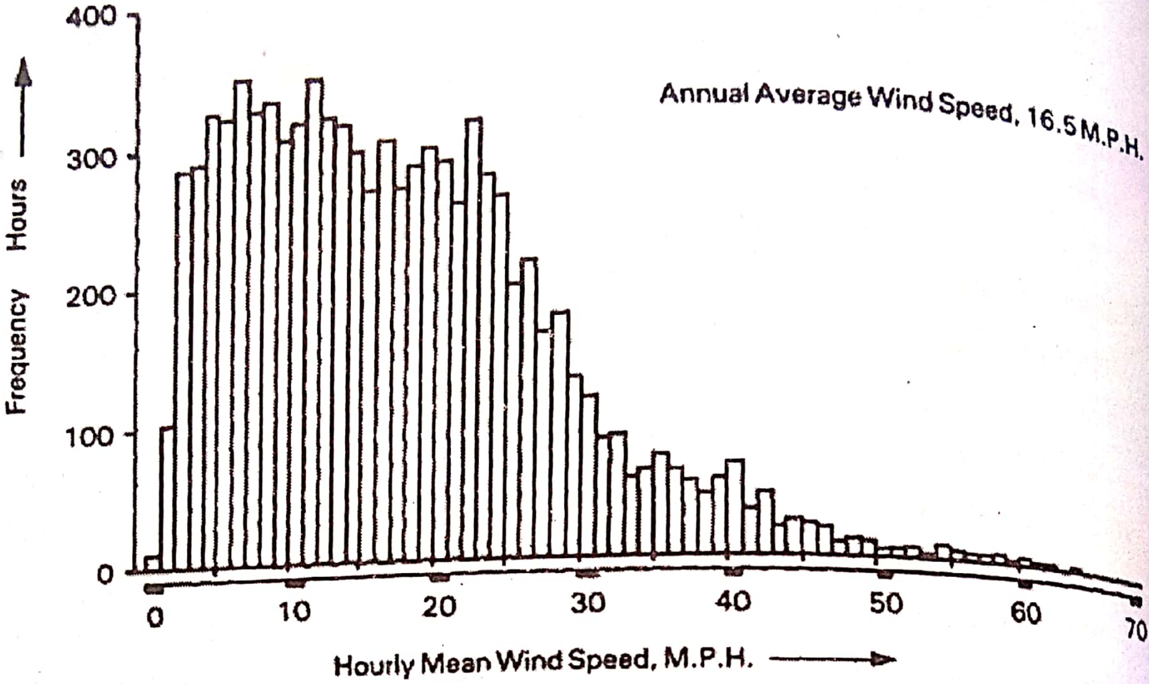


Figure 16.7: Wind Velocity-Frequency Histogram

When β = 1, the Weibull distribution equals the exponential distribution and a constant failure rate in time is observed. When $\beta > 1$, it indicates an increasing failure rate in time and for $\beta < 1$, the failure rate in time is decreasing. On the other hand, η is the time at which 63.2% samples are expected to fail. This is true for all Weibull distributions regardless of the shape parameter β. Irrespective of the value of β, setting t = 1 in equation 16.7 gives:

$$F(t) = 1 - \exp[-(1)\beta] = 0.632 \qquad 16.8$$

Weibull distribution providing certain parameters when are correctly selected, will produce a acceptable correlation with natural empirically measured wind regime curves. The analysis required is beyond the scope of this book. Therefore, the best information that is ever usually available will be an hourly-based wind frequency distribution curve for the site. Ideally, this should be combined with data giving the monthly mean wind speeds and the percentage of calm per month. For irrigation pumping it is of critical importance to consider the wind regime during the month of maximum water demand; an annual average does not suit this purpose.

16.6. Measurement of Wind Speed

Derived from the Greek word, "anemos" meaning wind, anemometer is an instrument used to measure wind speed. Anemometers measure the horizontal wind speed (velocity), which simply totals the kilometers (or miles) of wind run just as a car odometer totalizes kilometers of road run. By noting the time when each reading is taken, and dividing the difference between two readings by the time interval, it is possible to determine the mean wind speeds over the time period. This parameter is crucial for any wind site assessment. Cup anemometers are the general standard type of anemometer. They are robust and resistant to turbulence and skew winds caused by masts and traverses. Most anemometers are designed with cups mounted on short arms connected to a rotating vertical shaft as shown in figure 16.8. Some anemometers use a small propeller, but are less common.

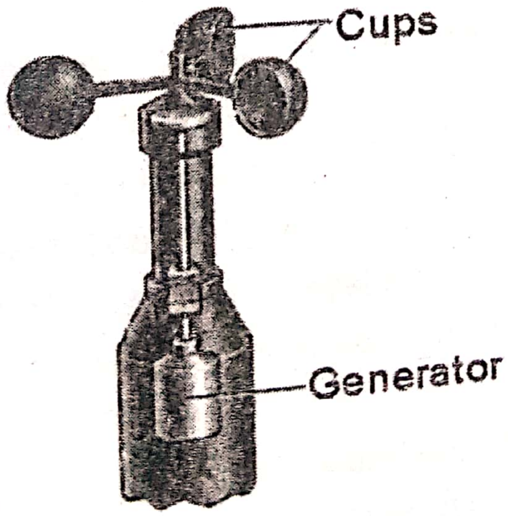


Figure 16.8: An Anemometer

The wind force acting on the cups rotates the generator, which produces a voltage that is proportional to the wind speed. The entire assembly is a turbine-generator system. The output of the generator is measured with the help of voltmeter (analog or digital), which can be calibrated directly in terms of wind speed. The anemometer thus rotates in the wind and generates a signal proportional to wind speed. The idea of anemometer is the same as that of a tachometer. In most cases the signal is electrical, although some anemometers produce mechanical signals. Wires lead from the anemometer to an indicator (display) or recorder that is made for indoor or outdoor use. Indicators give current information on a dial or digital display or with blinking lights. They present only visual wind values and do not have any storage capability. If data are to be collected, they require a person to monitor the system and manually record the data into a logbook. Indicators are impractical for most wind feasibility studies and in general are not recommended.

On-site wind measurements should be taken prior to deciding to design or purchase a wind turbine. The data collected will determine the wind resource and help with wind turbine selection and economic value. It is necessary to examine how the collected data will be used. This depends on the intended purpose of the wind turbine. If a wind turbine is being considered for annual electric power production, then the wind data will be used to estimate that production. In this case, mean wind speeds and wind speed distributions will be important. If, however, a wind turbine is intended to furnish power during periods of the peak demand, a more detailed evaluation will be needed. At a minimum, the variation of speed with time-of-day and season should be estimated, and possibly the duration of windless periods for applications where battery storage is to be used.

As a general rule, the more frequently data is recorded, the more expensive the recording equipment is and the more data there is to analyze. Hourly recording will suit the needs of virtually any application. Both short-term information, such as the diurnal speed variations and the duration of calm spells, and long-term information, such as monthly and annual averages, can be provided in this way. Daily recording is usually sufficient to characterize average wind conditions where hourly details are unnecessary. The longer the monitoring period, the much better are the results. Ideally, one full year, and preferably several years, of wind measurement is recommended. This will provide data for all the seasons, and on inter-annual changes, should the period be more than one year. Because of cost or scheduling problems, some designers may not wish to make lengthy measurements. Shorter-term measurements can still be of value, but they also will have greater limitations.

16.7. Wind Energy and Speed Distribution

Energy content of wind depends on the wind speed, which a function of height and geographical terrain. From the energy content, the power available can be calculated by using the usual relationship:

$$E = P \times T$$

Care should be taken in calculating the amount of energy available from the wind, as it is quite common to overestimate its potential. It is not advisable simply to take the average of the wind speeds throughout the year and use it to calculate the energy available from the wind because its speed is constantly changing and according to physical nature its power is proportional to the cube of the wind speed. It is advisable to weigh the probability of each wind speed with the corresponding amount of energy it carries. Experience shows that for a given height above ground, the frequency at which the wind blows with any particular speed follows a Rayleigh distribution, first introduced by Lord Rayleigh in 1880 in connection with the problem of interference of harmonic oscillations with spiral phases. The Rayleigh distribution is encountered in applications of probability theory, for example in radio engineering. The Rayleigh distribution can be used to model the velocity of particles whose velocity in the x and y directions are independent and follow a normal distribution. The Rayleigh distribution is a special case of Weibull distribution mentioned earlier and has a parameter β. The probability density function is:

$$P(x) = \frac{x}{\beta^2}\exp\left(-\frac{x^2}{2\beta^2}\right) \qquad 16.9$$

Where β is the parameter of the distribution and the cumulative distribution function $F(x)$ can be expressed as:

$$F(x) = 1 - \exp\left(-\frac{x^2}{2\beta^2}\right) \qquad 16.10$$

Figure 16.9 shows a typical wind speed distribution. The modal wind speed, that is the speed at which the wind most frequently blows, is less than the average wind speed which is the speed often quoted as representing the typical wind conditions.

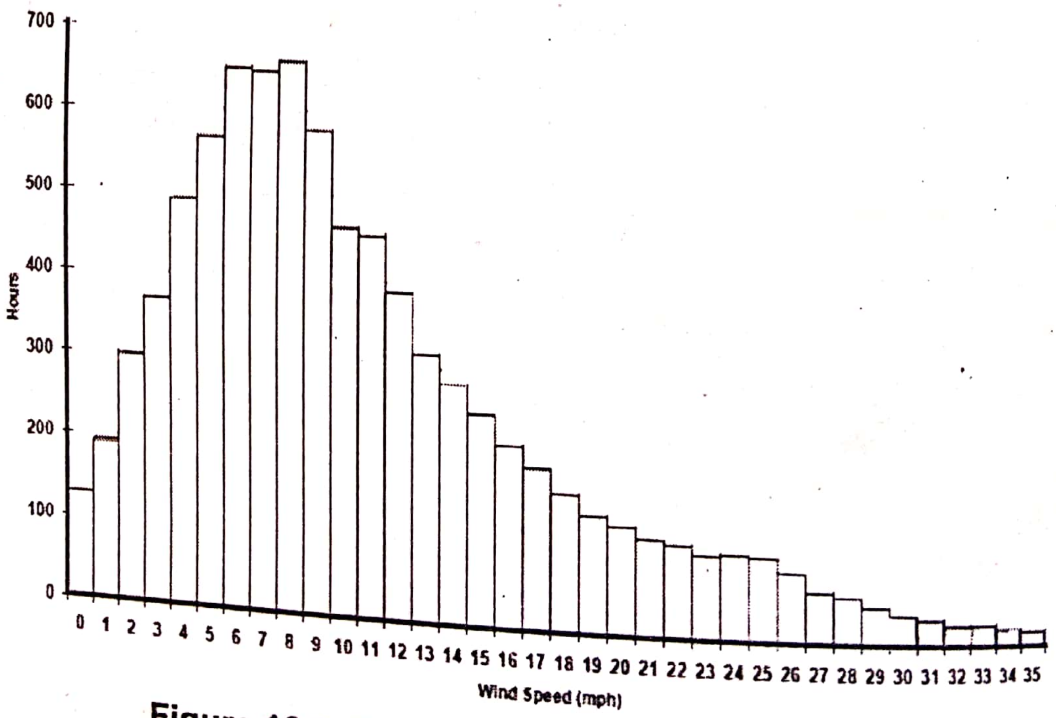


Figure 16.9: Typical Wind Speed Distribution

For reference, the average wind speed across the UK quoted by the Department of Trade and Industry (DTI) is approximately 5.6 meters per second at 10 meters above ground level (AGL). Published average wind speeds are only reliable for open rural environments. Wind speeds just above roof level in urban environments will be considerably less than the quoted averages because of turbulence and shielding caused by buildings and trees. A wind turbine sited below the ridge of a building or at a similar height in the garden of an urban dwelling as often shown in the product sales literature is unlikely to provide the energy levels claimed in the specifications. The distribution does not represent the energy content of the wind since this is proportional to the cube power of the wind speed. A distribution such as the one above is only valid for the prevailing wind conditions at a particular height above the ground. The histogram of figure 16.10 shows the resulting distribution of the wind energy content superimposed on the Rayleigh wind speed distribution of figure 16.9, which caused it. Unfortunately conventional wind turbines can capture not all of this wind energy.

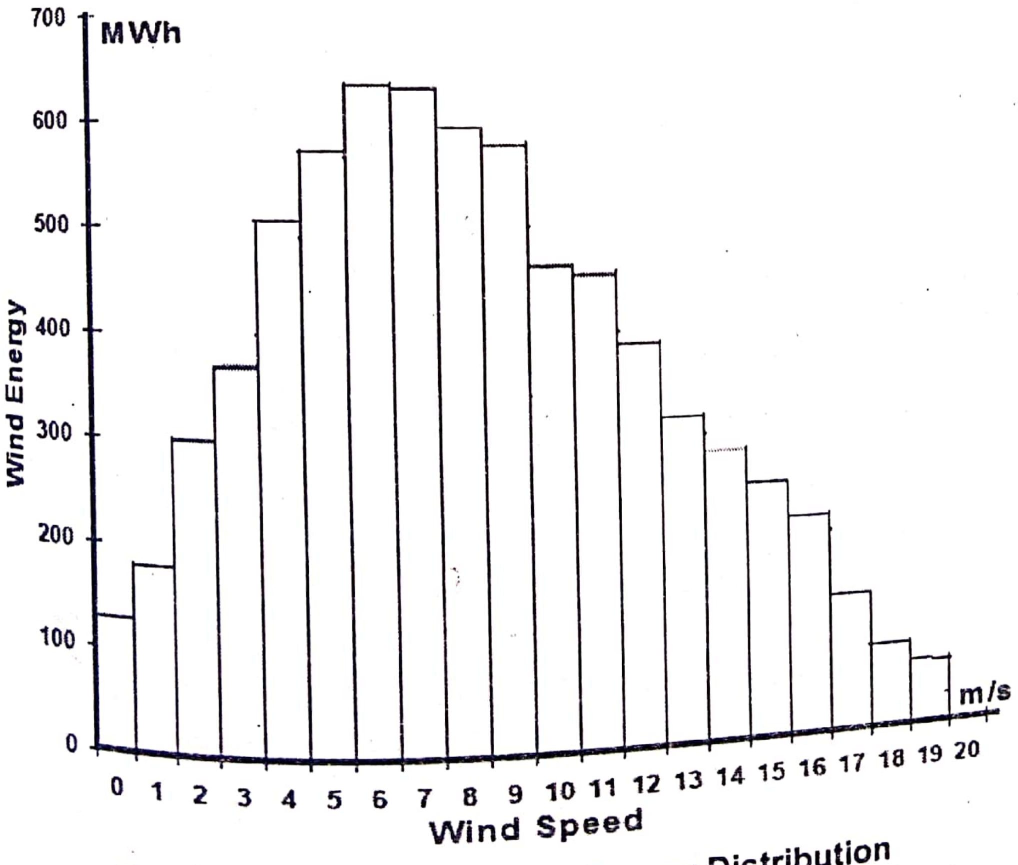


Figure 16.10: Typical Wind Energy Distribution

The peak wind energy occurs at wind speeds considerably above both the modal and average wind speeds since the wind energy content is proportional to the cube of its speed. Very little energy is available at low speeds and most of this will be needed to overcome frictional losses in the wind turbine. Energy generation typically does not cut in until wind is blowing at speeds of at least 3 m/s to 5 m/s. High wind speeds cause high rotation speeds and high stresses in the wind turbine which can result in serious damage to the installation. To avoid these dangerous conditions, wind turbines are usually designed to cutout at wind speeds of around 14 m/s either by braking or feathering the rotor blades allowing the wind to spill over the blades. Because of the upper speed limit at which the wind turbine can safely be used, it may capture only half or less of the available wind energy.

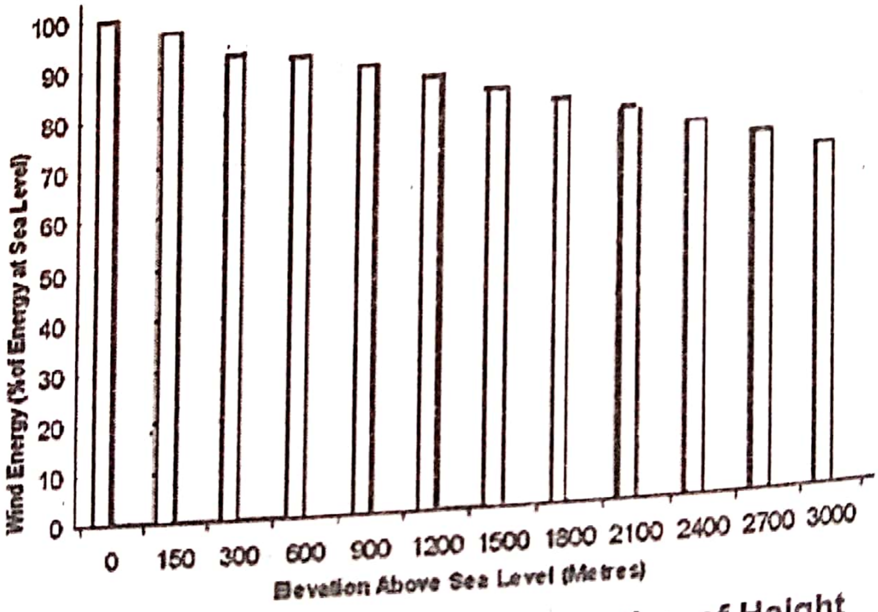


Figure 16.11: Wind Energy as a Function of Height

For a given wind speed the wind energy also depends on the elevation of the wind turbine above sea level. This is because the density of the air decreases with altitude and the wind energy is proportional to the air density. This effect is shown in the histogram of figure 16.11. For a given wind speed the wind energy density decreases with increases in altitude. However, at the same time the actual wind speeds tend to increase with height above ground level. Since the wind energy is proportional to the cube of the wind speed, the net effect is that wind energy tends to increase with the height above ground level. As the density of air decreases with altitude, the wind energy density also decreases. By contrast the available solar energy increases with altitude due to lower atmospheric absorption.

16.8. Available Theoretical Power

The power P available in the wind impinging on a wind driven generator can be obtained by knowing the kinetic energy of the wind, which is given by:

$$E = \frac{1}{2} m V^2 \qquad 16.11$$

Where m is the mass of striking wind stream and V is the velocity (speed) of the wind stream. The density of air ρ (averaging 1.225 kg/m^3 at sea level) is related to mass (mass per unit volume), so that equation 16.11 can be expressed as:

$$E = \frac{1}{2} \rho (volume) V^2$$

Considering an area A of the wind front intercepted by a rotor plate of length L on which the wind acts, the volume is then (A x L), so that:

$$E = \frac{1}{2} \rho A L V^2 \qquad 16.12$$

Dividing both sides of expression 16.12 by time t and using the definition of power (energy per unit time) and velocity (length per unit time), we have:

$$P = \frac{1}{2} A \rho V^3 \qquad 16.13$$

Equation 16.13 is applicable under ideal conditions and gives theoretical maximum power that can be obtained from a wind turbine by the action of wind stream. An ideal wind turbine with this maximum value is known as a Rayleigh-Betz machine. However, not all the energy can be recovered from a wind stream. A factor known as coefficient of performance K_p (sometimes known as power coefficient), which is dependent on the machine design is therefore incorporated in equation 16.13 to account for the non-ideal behavior of practical wind turbines. The theoretical maximum value for the coefficient of performance is 0.593. In practice the value of the maximum values of coefficient is in the range 0.25 to 0.45. In general, the larger the machine the higher is this value. Also the use of variable pitch rotors can optimize the coefficient of performance for a range of wind speeds. The maximum value of the coefficient has been set close to the modal wind speed for Rayleigh averages in the range 5 to 7 m/sec. The rotor design should be optimized for the site. Since wind turbines are to be incorporated to drive a generator to produce electricity, a conversion efficiency η is also incorporated in equation 16.13. Conversion efficiency is the fraction of the energy available at the turbine hub, which is converted into electricity. For simplicity, the value has been set at 0.7. In practice, the value is composed of two elements, mechanical and electrical. The mechanical element is quite high with losses coming from items like bearings, gearboxes (if any) etc; whilst the electrical part would come from the specification of the generator. Therefore equation 16.13 can be modified as:

$$P = \frac{1}{2} K_p \eta A \rho V^3 \qquad 16.14$$

From equation 16.14, it can be seen that the power is proportional to area swept by the blades, the density of the air and to the cube of the wind speed. Thus doubling the blade length will produce four times the power and doubling the wind speed will produce eight times the power. It must also be noted that the effective swept area of the blades is an annular ring, not a circle, because of the dead space around the hub of the blades. Too little wind and they are unable to power sufficient sustained power to overcome frictional losses in the system. Too much and they are susceptible to damage due to excessive mechanical operations. Between these extremes, cost efficient installations have been developed to extract energy from the wind.

An important factor as to how much power wind turbine can produce is governed by the height of its installation tower. As mentioned earlier, the wind speed is dependent on the height, which is high for greater heights. Since the power available in the wind is proportional to the cube of its speed, this means that if wind speed doubles, the power available to the wind generator increases by a factor of 8. The power that can be obtained from a particular wind speed is displayed in the graph of figure 16.12, which shows the power density with the wind speed.

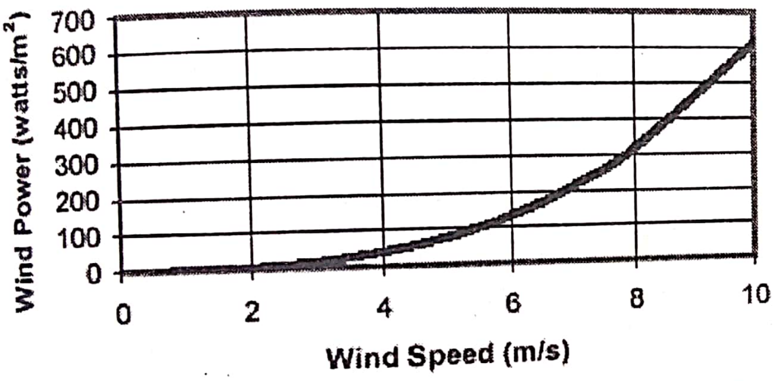


Figure 16.12: Relationship between Wind Speed and Wind Power

Example 16.5: Calculate the electrical power that can be obtained from a wind blowing at a speed of 5m/s incident on a three rectangular blade each of size 3m x 0.5m of a wind turbine. Assume coefficient of performance and conversion efficiency of 0.7 and 0.45 respectively.

Given that:

V = 5m/s

K_p = 0.7

η = 0.45

The sweep area of the blades is: $A = \pi(3)^2 =$ 28.26 m². The air density is 1.225kg/m³, using:

$$P=\frac{1}{2}K_p\eta A\rho V^3 \text{ Watts}$$

$$P=\frac{1}{2}\times 0.7\times 0.45\times 28.26\times 1.225\times (5)^3 = \mathbf{681\ W\ or\ 0.681\ kW}$$

Example 16.6: Calculate the electrical power that can be obtained from a turbine with swept area of 12.5 m^2 from a wind blowing at an average speed of 4.7 knots, measured at a reference height of 10m in a region of smooth plain geographical terrain. The turbine is pole mounted and is located at a height of 55 meters above the ground surface. Assume coefficient of performance and conversion efficiency of 0.7 and 0.45 respectively.

Given that:

$A = 12.5\ \text{m}^2$

$K_p = 0.7$

$\eta = 0.45$

Since the average wind speed measured at the surface is 4.7 knots, which is 4.7 x 0.514 = 2.41 m/s (1 knot = 0.514 m/s). The height of the wind turbine location is 55 meters above the ground. The roughness length z_0 from table 16.2 for a smooth and even terrain is 0.0024. Therefore using:

$$V = V_{ref}\frac{\log_{10}(z/z_0)}{\log_{10}(z_{ref}/z_0)}$$

Or $$V = 2.41\times\frac{\log_{10}(55/0.0024)}{\log_{10}(10/0.0024)} = 2.9\ \text{m/s} \approx 3\ \text{m/s}$$

This can also be obtained by using Elliot's formula as:

$$V = V_{ref}\left(\frac{h}{h_{ref}}\right)^{0.143}$$

1/7

$$V = 2.41\times\left(\frac{55}{10}\right)^{0.143} = 3.07\ \text{m/s} \approx 3\ \text{m/s}$$

To determine the electrical power, using:

$$P=\frac{1}{2}K_p\eta A\rho V^3 \text{ Watts}$$

$$P=\frac{1}{2}\times 0.7\times 0.45\times 12.5\times 1.225\times (3)^3 = \mathbf{65.11\ Watts}$$

It can be noted from the two examples that the potential in the wind to produce power is rather less as compared to the conventional systems. The only factor is the cost of fuel, for example in thermal power stations.

16.8. Practical Power and Conversion Efficiency

German aerodynamicist Albert Betz showed that a maximum of only 59.3% of the theoretical power could be extracted from the wind, no matter how good the wind turbine is, otherwise the wind would stop when it hit the blades. He demonstrated mathematically that the optimum occurs when the rotor reduces the wind speed by one third. After inefficiencies in the design and frictional losses are taken into account the practical power available from the wind will rarely exceed 40% of the theoretical power. Converting this wind power into electrical power incurs further losses of 10% or more in the drive train and the generator and another 10% in the inverter and cabling such that ultimately, the wind turbine will capture only about 30% to 35% of the wind energy available. It must be noted that the power output from commercially available wind turbines is usually specified at a steady, gust free wind speed of 12.5 m/s. In the many locations, particularly urban installations, the prevailing wind will rarely reach this speed. The coefficient of performance and conversion efficiency can be combined to yield wind turbine efficiency η_T, so that equation 16.14 can be expressed as:

$$P=\frac{1}{2}\eta_T A\rho V^3 \qquad 16.15$$

The efficiency depends on the tip speed ratio. The tips speed ratio (TSR) is the ratio of the speed at the tip of the wind turbine blade to the wind speed and is given by:

$$TSR=\frac{wR}{V} \qquad 16.16$$

Where w is the angular speed, R is the rotor radius and V is the wind speed. The rotation speed can be obtained from the mechanical power of the turbine given by:

$$P_{mech} = \frac{1}{2} J w^2 \qquad 16.17$$

Where J is the moment of inertia, which can be determined for a turbine with blades that are in the form of parallelepiped of a horizontal axis as:

$$J = \frac{N_B \rho_B (L_B W_B t_B) L_B^{\,2}}{3} \qquad 16.18$$

Where N_B are the number of rotor blades, ρ_B is the density of the rotor blade material, L_B is the blade length, W_B is the width of the blade and t_B is the thickness of the rotor blade. No turbine can capture more than 16/27 (59.3%) of the kinetic energy of the wind according to German physicist, Albert Betz. This limit is known as the 'Betz Limit' and has nothing to do with inefficiencies in the generator, but how turbines actually work. Wind turbines extract energy and so slow down the wind passing through them. For a wind turbine to extract 100% of the energy it would need to stop 100% of the wind. If it did this it would then stop working. Instead it extracts enough energy to still allow the wind to continue to pass through it. The efficiency in relation to TSR for various types of turbines is given in table 16.3.

Example 16.7: Compute the ideal efficiency of a three blade aluminium alloy wind turbine with the following specifications:

- Blade length = 3.5m
- Blade width = 1.2m
- Blade thickness = 0.2m
- Hub diameter = 0.75m

The installation is used for an average wind speed of 20mph. Assume the density of aluminium alloy used to be 2700 kg/m^3.

Given the specifications:

$L_B = 3.5$m

$W_B = 1.2$m

$t_B = 0.2$m

$D_H = 0.75$m (hub diameter)

The efficiency can be calculated on the basis of TSR. For this purpose, the rotation speed of the turbine must be determined. From equation 16.15, the radius of the rotor R has to be determined. According to the geometry of the turbine system, the blades are mounted on a hub of 0.75 m diameter in a fashion that each blade is at an angular displacement of 120 degrees with respect to each other. The radius of rotor is:

$$R = L_B + (D_H / 2) = 3.5 + 0.375 = 3.875 \text{ m}$$

Therefore the speed of rotation w can be obtained from the knowledge of moment of inertia of the turbine system, which depends on its dimensions and the mechanical power output of the turbine. The moment of inertia can be obtained by using:

$$J = \frac{N_B \rho_B (L_B W_B t_B) {L_B}^2}{3}$$

$$J = \frac{3 \times 2700 \times (3.5 \times 1.2 \times 0.2) \times (3.5)^2}{3} = 27783 \text{ kg-m}^2$$

Under ideal conditions, the mechanical power developed by the turbine is same as the wind power, thus equating equations 16.12 and 16.17, we have:

$$\frac{1}{2} A \rho V^3 = \frac{1}{2} J w^2$$

From which the angular velocity of the turbine can be obtained as:

$$w = \sqrt{\frac{A \rho V^3}{J}}$$

Or
$$w = \sqrt{\frac{(3.5\times1.2)\times1.225\times(8.8)^3}{27783}} = 0.355 \text{ rads/s}$$

Therefore using:

$$TSR = \frac{wR}{V}$$

$$TSR = \frac{0.355\times3.875}{8.8} = 0.156$$

From table 16.3, we note that the TSR is less than 0.5, so that using:

$$\eta = 0.658(TSR) + 0.023$$

$$\eta = 0.658(0.156) + 0.023 = \mathbf{0.125 \text{ or } 12.5\%}$$

Table 16.3: TSR and Efficiency of Different Types of Wind Turbines

Type of Wind Turbine	TSR	Efficiency
American Multi-blade	TSR ≤ 1.75	$-0.39(TSR)^2 + 0.66(TSR) + 0.026$
	TSR > 1.75	0
Darrieus (VAWT)	TSR < 4.6	0
	4.6 < TSR < 6.86	$-0.078(TSR)^2 + 0.92(TSR) - 2.35$
	TSR > 6.86	0
Three Blade	TSR < 2.95	0
	2.95 ≤ TSR ≤ 5.4	$-0.02(TSR)^2 + 0.18(TSR) + 0.023$
	TSR > 5.4	0
Ideal	TSR < 0.5	$0.658(TSR) + 0.023$
	0.5 ≤ TSR < 1.0	$0.196(TSR) + 0.232$
	1.0 ≤ TSR < 1.5	$0.104(TSR) + 0.324$
	1.5 ≤ TSR < 2.5	$0.055(TSR) + 0.399$
	2.5 ≤ TSR < 4.0	$0.022(TSR) + 0.481$
	TSR > 4.0	$0.0041(TSR) + 0.5532$

mple 16.7: Design a three-blade wind turbine by choosing TSR of 3. Work out suitable *ensions and determine* its output power. If the turbine is to be installed at a height of 50 *eters for the generation* of electricity for wind speed measured in the geographical even and *t region* at a height of 10 meters of 22mph, determine the electric power that can be *oduced.*

iven that:

TSR = 3; for a three blade turbine given in question

V_{ref} = 12 mph

h_{ref} = 10m

According to the information given in table 16.3, for TSR = 3, the efficiency can be determined by using:

$$\eta = -0.02(TSR)^2 + 0.18(TSR) + 0.023$$

$$\eta = -0.02(3)^2 + 0.18(3) + 0.023 = 0.383 \text{ or } 38.3\%$$

The wind speed of 22 mph at a reference height of 10 m given in question can be used to obtain the wind speed at a height of 50 m by using equation 16.3. For smooth and plain geographical terrain the value of n from table 16.1 gives; n = 0.1, therefore:

$$V = 12 \times \left(\frac{50}{10}\right)^{0.1} = 14.1 \text{ mph or } 6.26 \text{ m/s}$$

The radius R of the turbine can be calculated by making a compromise between the rotation speed w and R by using: $TSR = \frac{wR}{V}$

Or $$R = \frac{TSR \times V}{w}$$

Choosing speed of rotation of 1 rps, suitable in order to avoid any excessive vibrations, the radius R is then:

$$R = \frac{1 \times 6.26}{2.5} = 2.5 \text{ m}$$

For rectangular blade system, if hub radius is 0.25m, the length of the blade is:

$$L_B = 2.5 - 0.25 = \mathbf{2.25\ m}$$

Choosing a width of: W_B = **0.5 m** and thickness t_B = **5 cm** for aluminium alloy, the sweep or capture area A will be:

$$A = \pi(2.5)^2 = 19.62 \text{ m}^2$$

The electrical power in Watts that can be obtained from the turbine can be calculated by using:

$$P = \frac{1}{2}\eta A\rho V^3 = \frac{1}{2} \times 0.383 \times 19.62 \times 1.225 \times (6.26)^3 = \mathbf{1130\ W\ or\ 1.13\ kW}$$

16.10. Wind Turbines

Wind turbines that are used in wind power generation are usually of two distinctive types (see figure 16.13); (a) turbines that rotate around a horizontal axis, referred to as horizontal axis wind turbine (HAWT) and (b) turbines that rotate around a vertical axis, referred to as vertical axis wind turbine (VAWT). Horizontal axis turbines are more common and need to be faced directly at the wind stream. Vertical axis turbines work whatever direction the wind is blowing, but require a lot more ground space to support their guy wires than horizontal axis wind turbines.

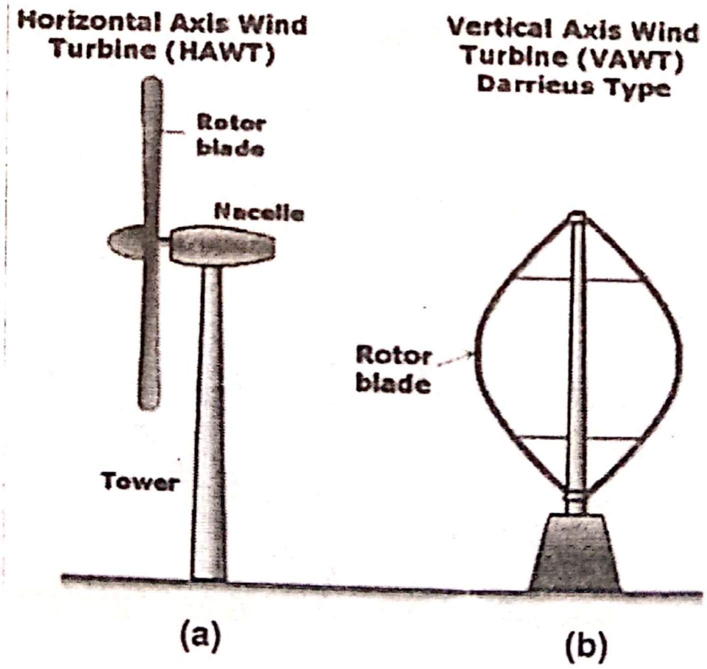
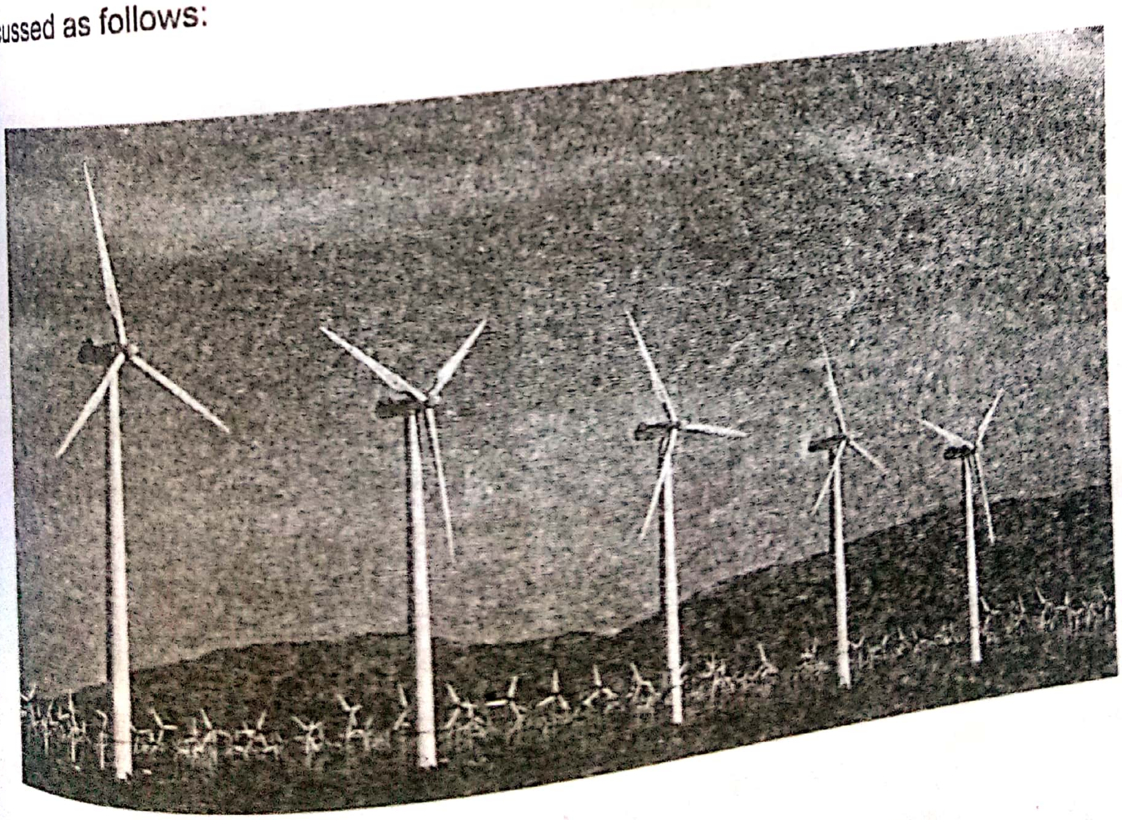


Figure 16.13: Wind Turbines

The wind is made up of real matter with mass and when mass is moving, it possesses kinetic energy. Wind turbines work by converting the kinetic energy of the wind into torque that causes the wind turbine to rotate. As the wind causes the wind turbine to turn, the energy in the wind is reduced. The energy that is removed from the wind is converted into mechanical energy that is used to drive an electrical generator and then converted into electrical energy. Wind turbines that are used to generate electricity come in a wide variety of sizes. Large wind turbines, which are usually installed in clusters called wind farms (see figure 16.14), can generate large amounts of electricity producing hundreds of megawatts; enough to power hundreds of homes. Small wind turbines, which are generally defined as producing no more than 100 kW of electricity, are designed to be installed at homes, agricultural farms and small commercial centers; either as a source of backup electricity, or to offset use of utility power and reduce electricity bills. Very small wind turbines (20-500 watt units) are used to charge batteries for sailboats and other recreational uses. On the basis of aerodynamics, wind turbines can be classified as lift type and drag type, which are briefly discussed as follows:



Lift Type: This is a common type of modern horizontal axis wind turbine. The rotor blades of this type of turbine have a similar design as that of an airplane wing. As the air blows on both side of the blade, it takes the air along to travel across the leading edge creating a lower air pressure and higher air pressure on the tailing edge. This pressure difference 'pulls' and 'pushes' the blade around thus enabling it to rotate. Lift type blades have much higher rotational speeds than drag type, which make them well suited for generating electrical power.

Drag Type: The first type of wind turbines created used a drag design. This type of wind turbine uses the force of the wind to push the blade. The VAWT of Savonius type is a perfect example of this design type (see figure 16.16), the wind is resisted by blade and the force of wind on it pushes it around thus enabling it to rotate. This design normally creates a slower rotational speed with a higher torque than a lift type design. This design has been used for centuries for milling, sawing, pumping, but rarely used for energy generation on large scale.

16.11. Components of Wind Turbine

The Hub: The hub is the centre part of the rotor made of cast iron or steel to which the rotor blades are attached. In simple designs, the rotor blades are directly bolted to the hub and hence are securely attached but can be removed directly. In other designs, the rotor blades are bolted to the pitch mechanism, which is in turn bolted to hub. This arrangement, allows the rotor blades to adjust their angle of attack according to the wind speed to control their rotational speed. Figure 16.15 shown a part of the blade attached to the hub.

Rotor: The rotor is the main element of a wind turbine, which consists of multiple blades attached to a hub. It is the turbine component responsible for collecting the energy present in the wind and transforming this energy in providing mechanical motion. As the overall diameter of the rotor design increases, the of energy that the rotor can extract from the wind also increases. es are therefore often designed on the basis of certain rotor diameter and ergy that can be drawn from the wind.

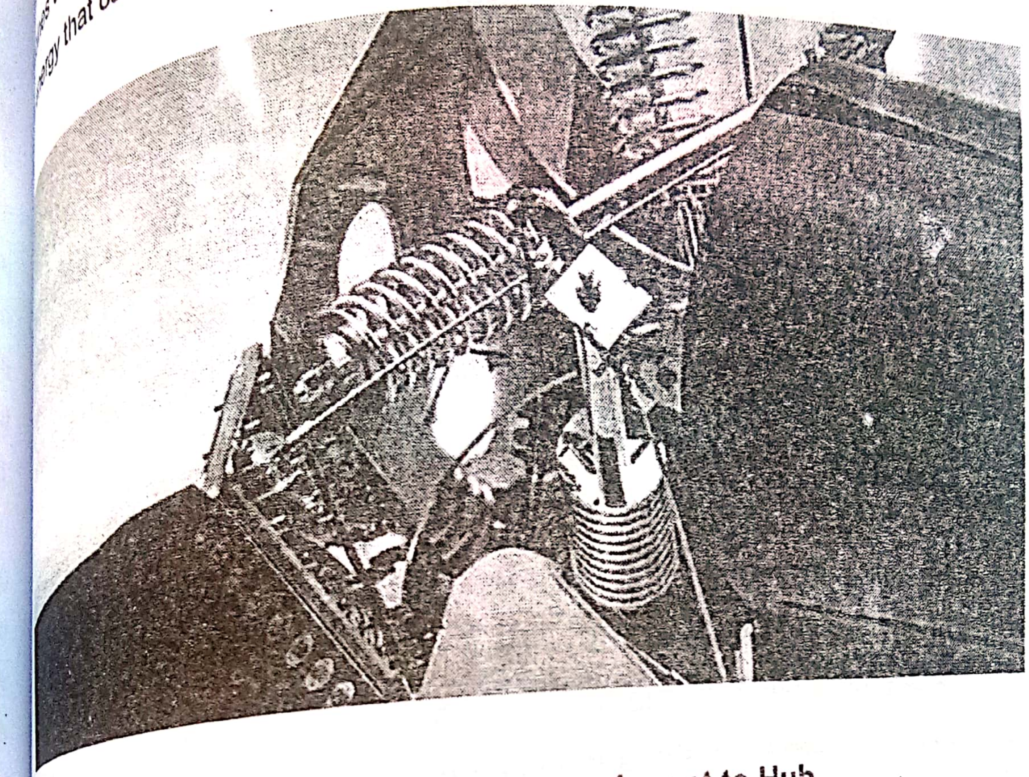


Figure 16.15: Blades Attachment to Hub

Blades: Rotor blades are a crucial part of a wind turbine. They are mainly made of aluminium, fiber glass or carbon fiber because they are tough and lighter in weight, thus provides better strength to weight ratio. The design of the individual blades also affects the overall design of the rotor. The profile of the rotor blades plays a key role in extracting the kinetic energy of the wind and transforming to produce rotation of the rotor. The profile is similar to that of airplane wings. Rotor blades utilize the same principle of the aerofoil as discussed earlier; the incident wind stream produce lift below the wing, the stream of air produces overpressure above the wing. The combined effect of these forces makes the rotor to rotate. The process of converting the wind into mechanical energy starts with the wind turbine blades. There are two different types of blade designs, lift type and drag type, which then classify the turbine accordingly as already discussed.

Rotor Shaft: The shaft is the 'backbone' of the turbine that gets turned by the turbine blades. It in turn rotates the electric generator, which is mechanically coupled either directly or through a gearbox.

Electric Braking: Braking of a small wind turbine can be accomplished by dumping energy from the generator into a resistor bank, thus converting the kinetic energy of the turbine rotation into heat. This method is useful if the kinetic load on the generator is suddenly reduced or is too small to keep the turbine speed within its allowed limit. Cyclic braking, however, causes the rotor to slow down, which increases the stalling effect thus reducing the efficiency. This method allows the turbine rotation to be kept at a safe speed in faster winds while maintaining (nominal) power output. This method, however, is not applied on large grid-connected wind turbines.

Mechanical Braking: A mechanical braking system is normally placed on the high speed shaft between the gearbox and the generator. There are some turbines in which the brake system is mounted on the low speed shaft between the turbine and gearbox. In addition, a braking system incorporating mechanical drum, brake or disk brake system is used to stop turbine in emergency situation such as; in the event of extreme gust or over-speed. This brake system is also used as a secondary means to hold the turbine at rest for maintenance, the primarily brake being the rotor lock system. Such brakes are usually applied only after blade furling and electromagnetic braking have reduced the turbine speed, as the mechanical brakes can create a fire inside the nacelle if used to stop the turbine from full speed. Also the load on turbine increases if brake is applied on rated speed. These kind of mechanical brakes are driven by hydraulic system and connected to main control box.

Gearbox: The main function of the gearbox is to convert low rotational speed of the shaft high rotational speed of the generator. The gearbox consists of gear stages for provide an appropriate gear ratio. The types of gear stages are the

Plantary, helical, spure and worm types. Two or more gear types may be combined in multiple stages. They are made up of aluminium alloys, stainless steel and cast iron.

Generator: The conversion of rotational mechanical energy to electrical energy is accomplished by the generator. Different types of generator have been used in wind energy system over the years. In large commercial size horizontal-axis wind turbines, the generator is mounted in a nacelle at the top of a tower, behind the hub of the turbine rotor. Typically wind turbines generate electricity through asynchronous machines that are directly connected with the electricity grid. Usually the rotational speed of the wind turbine is slower than the equivalent rotation speed of the electrical network; typical rotation speeds for wind generators are 5-20 rpm. Therefore, a gearbox is inserted between the rotor hub and the generator. This also reduces the generator cost and weight. Generators can be either variable or fixed speed. Variable speed generators produce electricity at a varying frequency, which must be corrected to power frequency (50 Hz or 60 Hz) before it is fed onto the grid. Fixed speed generators do not need to be corrected, but are not as able to take advantage of fluctuations in wind speed.

Tower: The main function of the tower is to support the nacelle and turbine rotor and provide the rotor with the necessary elevation to reach better wind conditions. Most towers are made of steel.

Nacelle: The nacelle houses a generator and gearbox. The spinning blades are attached to the generator through a series of gears. The gears increase the rotational speed of the blades to the generator speed of over 1500 rpm. As the generator spins, electricity is produced.

Guy Wires (only in vertical axis wind turbine): Vertical axis wind turbine normally needs guy wires to keep the rotor shaft in a fixed position and minimizes possible mechanical vibrations.

16.10.1. Vertical Axis Wind Turbine (VAWT)

In vertical axis wind turbine the main rotor shaft arranged vertically as shown in figure 16.13(b). The main advantage of this arrangement is that the wind turbine does not need to be pointed into the wind. This is an advantage on sites where the wind direction is highly variable or sites with turbulent winds. With a vertical axis, the generator and other primary components can be placed near the ground, so the tower does not need to support it, also makes maintenance easier. The main drawback of a VAWT is that it generally creates drag when rotating into the wind. It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine. Air flow near the ground and other objects can create turbulent flow, which can introduce problems of vibration, including noise and bearing wear which may increase the maintenance cost and shorten its service life. However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof and can double the wind speed at the turbine. If the height of the rooftop mounted turbine tower is approximately 50% of the building height, this is near the optimum for maximum wind energy and minimum wind turbulence. The use of guy wires is necessary, which provides additional support and secure the shaft assembly in a fixed position thus minimizing vibrations. VAWT are of two types, which are discussed in the following sections.

The Darrieus Type: The Darrieus wind turbines was patented in the United States by G. J. M. Darrieus in 1931. A Darrieus type of VAWT is shown in figure 16.16, which has a peculiar shape called troposkein, from the Greek for turning rope. The blades take the shape of a jumping rope experiencing high centrifugal forces. Darrieus wind turbines are commonly called 'Eggbeater' turbines, because they look like a giant eggbeater.

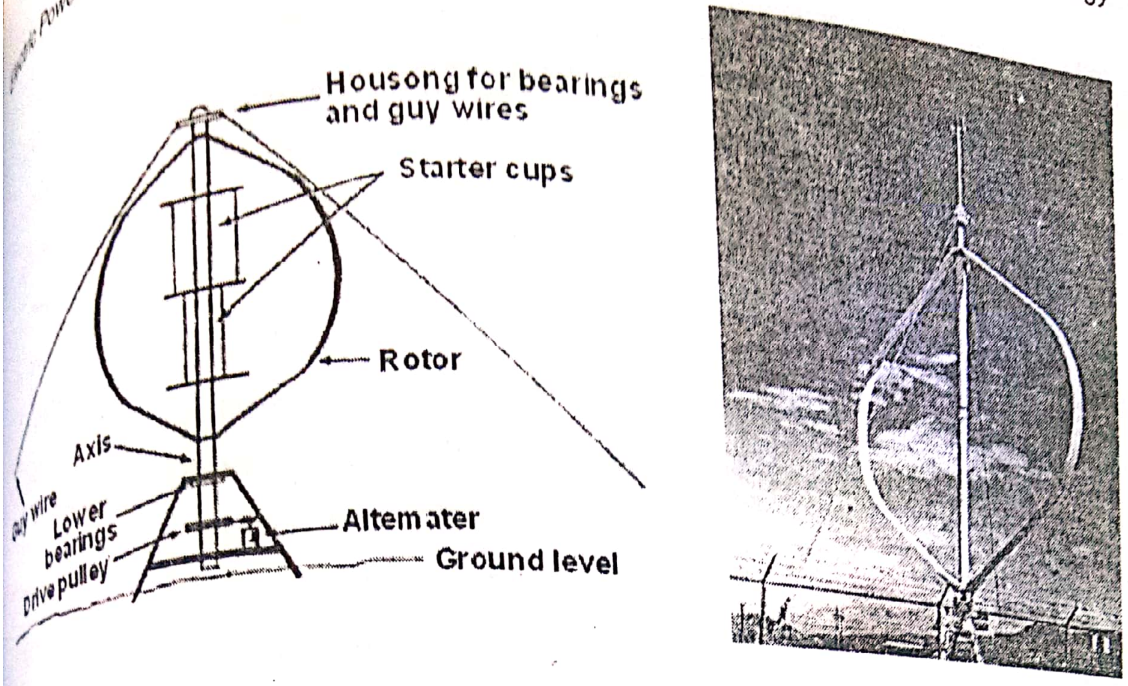


Figure 16.16: The Darrieus Type Turbine

The basic Darrieus turbine design is made up of a number of hydrofoils, which rotate about an axis in an oncoming flow. The combination of the blade's instantaneous velocity and the oncoming flow velocity produces a resultant velocity, which acts at an angle of attack on the blade. According to the aerodynamics, this resultant velocity produces a perpendicular lift and a parallel drag. If the angle of attack is greater than the angle subtended by the lift to drag ratio then a positive torque and power will be produced. By using a symmetrical hydrofoil, positive torque can be produced when the angle of attack becomes negative, which means that the turbine rotates in the same direction with flow from either direction. All channels have a velocity profile with slower flow at the base and faster flow at the surface, which favor one flow direction, but has a relatively small effect on the turbine performance.

Since the blade operates in almost pure tension, relatively light, inexpensive blades are sufficient. The power train, generator, and controls are all located near ground level, hence are easier to construct and maintain. They have good efficiency, but produce large torque ripple and cyclic stress on the tower, which can contributes to excessive vibrations and poor reliability. The torque ripple is reduced by using three or more blades which also results in a higher solidity for the rotor. Solidity is measured by blade area over the rotor area. Since the starting torque is very low, this type of turbine is therefore not self starting. This requires an external starting source, which is the major disadvantage of Darrieus turbine. Thus if the turbine has stopped during a period of low wind speeds, it will not usually start when the wind speed increases unless an external starting source is incorporated. Starting is usually accomplished by an induction motor connected to the local utility network. This may not necessarily be a major. disadvantage because the same induction motor can be used as an induction generator to supply power to the utility network when the turbine is at operating speed. For these reasons, induction machines are widely used as wind turbine generators. The efficiency is nearly as good as that of the horizontal axis propeller turbine, so the Darrieus holds considerable promise as a cost effective turbine.

The Savonius Type: Another type of Vertical axis wind turbine developed in Finland by S. J. Savonius in 1922; hence the name. This is another vertical axis machine which needs no orientation into the wind. A Savonius is a drag type turbine; they are commonly used in cases of high reliability in many things such as ventilation and anemometers. Because they are a drag type turbine they are less efficient than the common HAWT. Savonius are excellent in areas of turbulent wind and are self-starting. Figure 16.17 shows a Savonius type of wind turbine. It essentially consists; typically of two or three blades, curved to form a convex and concave side. The blade assembly is mounted on a shaft that rotates on a vertical axis. The entire system if mounted on a supporting structure. A Savonius turbine is a drag-type turbine that captures the wind through the use of two or three cups, similar to an anemometer, a device that measures wind speed. In both cases wind turns the cup.

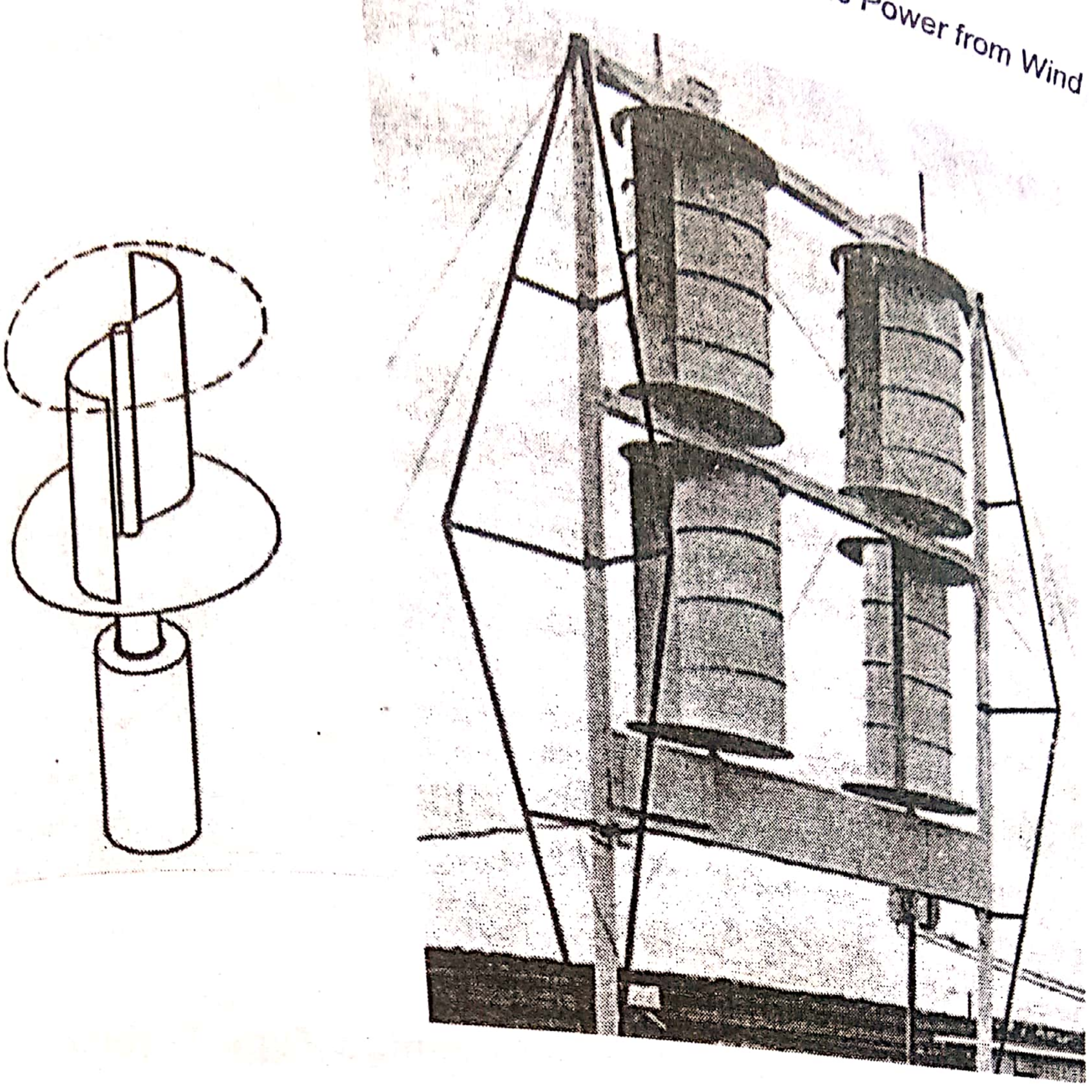


Figure 16.17: The Savonius Type

As illustrated in figure 16.18, the wind stream incident on the turbine blades will produce a force, which is proportional to the wind speed. The force produces torque on the blade making it to rotate. Because of the shape of the blades, most of the wind force is dispersed when it strikes the concave portion of the blade. Though a small drag will be exerted, but due to the reaction force offered by the wind moving along the convex surface. Neither one can turn faster than the speed of the wind. For wind speed the rate of turning translates into speed. The turning generates mechanical energy and electricity in the Savonius turbine. The Savonius has an efficiency rating of 15%, reflecting the amount of wind energy converted to electrical energy and is simple to construct. One major drawback to the Savonius use on any large scale is its slow turning rotation, which requires a manual start. That limits the amount of electricity it can generate. Because the Savonius cannot turn faster than the wind speed, the rotor functions during conditions of little or turbulent wind, another good feature for home use where wind availability is unpredictable.

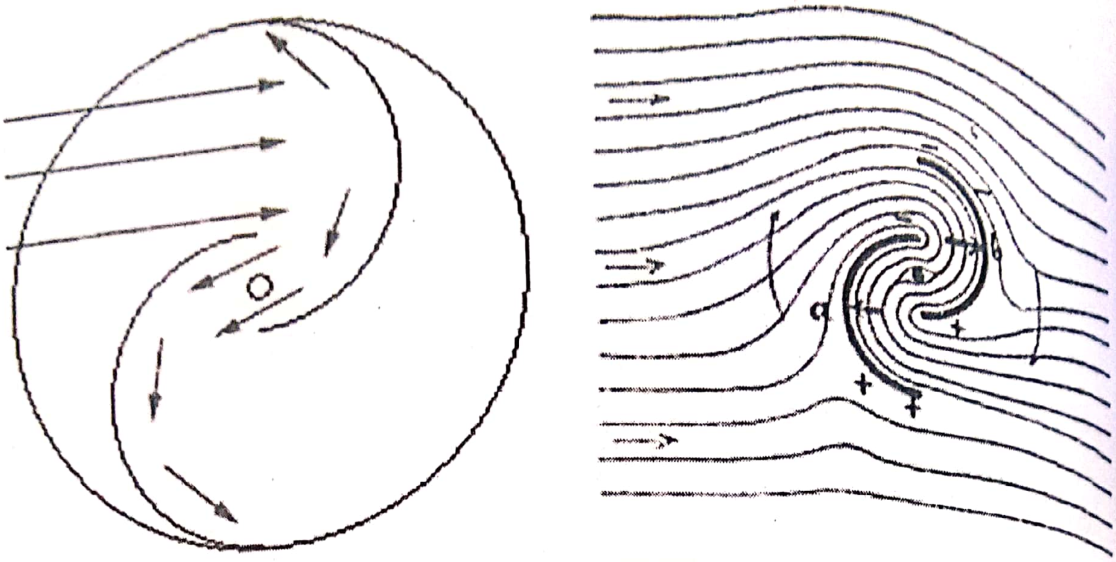


Figure 16.18: Air Flow in Savonius Type Turbine

According to the Conserve Energy Future website, one advantage of vertical axis wind turbines is easier maintenance. This refers to the fact that all the working parts are at ground level. No climbing tall towers to reach the blades. Another advantage involves placement. No calculations for wind direction and speed are required. Savonius type turbines will capture the wind from any placement. Its small rotation translates into quiet operation that will produce small but steady electricity.

16.10.2. Horizontal Axis Wind Turbine (HAWT)

The horizontal axis wind power turbines are mounted on top the tower along with its main rotor and the electrical generator as shown in figure 16.19. They are pointed into the wind and may have a wind sensor coupled with a servo motor for change of direction. They are also equipped with a gearbox for changing the slow rotation of the rotor or the blades into a faster rotation suitable the electrical power generation. Contemporary wind turbines come with self-justed gears, eliminating the need for the heavy gearbox. The HAWT turbines e usually pointed upwind to catch the turbulence which is produced behind the wer while the turbine blades are purposely placed further away from the tower s also somewhat tilted to avoid accidental contact with the tower. Apart from the HAWT turbines described above, downwind turbines are also in use since these urbines do not require any additional mechanism to keep them in line with the wind. Also, their blades are more resilient than the upwind types, thus allowing them to adapt to the occasional high winds encountered by them.

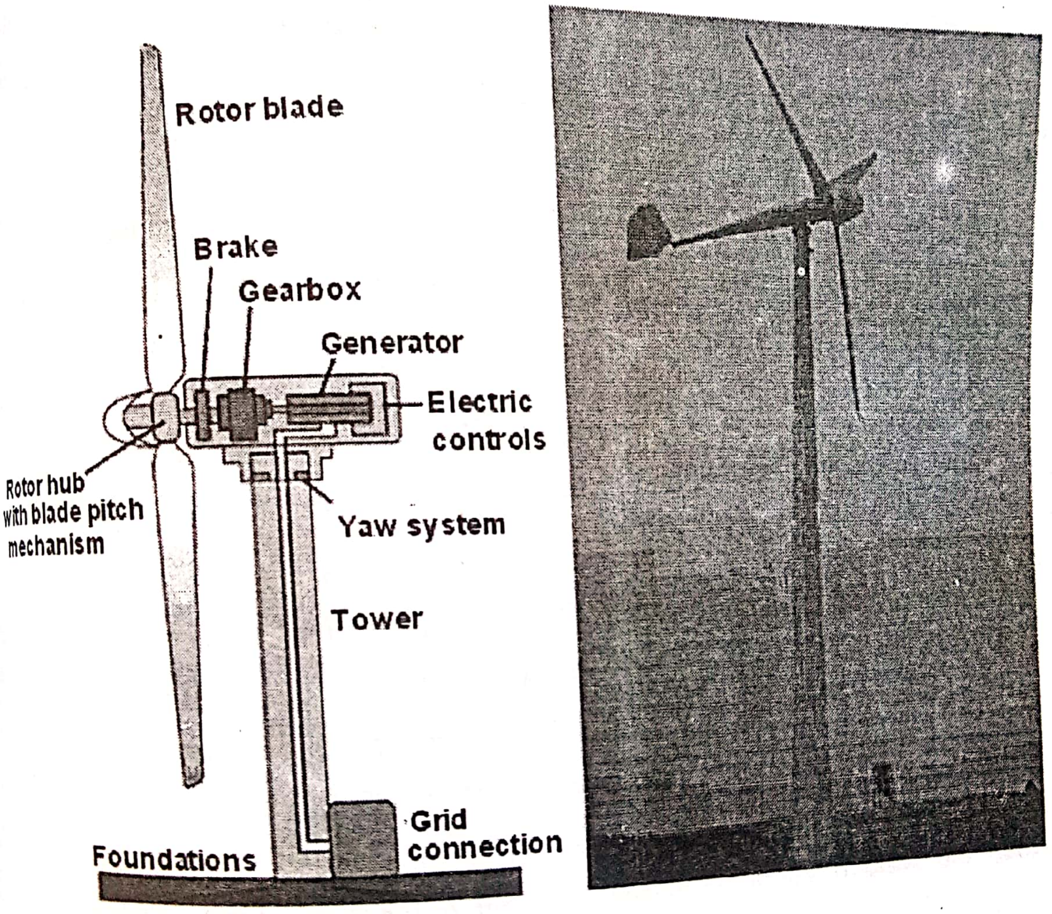


Figure 16.19: Horizontal Axis Wind Turbine

Large rotor blades are necessary to intercept the maximum air stream but these give rise to very high tip speeds. The tip speeds however must be limited, mainly because of unacceptable noise levels, resulting in very low rotation speeds, which may be as low as 10–20 rpm for large wind turbines. The operating speed of the generator is, however, is much higher, determined by the number of its magnetic pole pairs and the frequency of the grid electrical supply. Consequently a gearbox must be used to increase the shaft speed to drive the generator at its synchronous speed. Grid connected systems are dimensioned for average wind speeds 5.5 m/s on land and 6.5 m/s offshore where wind turbulence is less and wind speeds are higher. While offshore plants benefit from higher sustainable wind speeds, their construction and maintenance costs are higher.

Wind generators act on the power of the wind. Their extra long blades or rotors catch the wind as it hits them and they start spinning. This spinning movement, similar to a hydroelectric system, is transformed into electrical energy produced by a generator coupled to it. However, the quantum of power transferred to a wind turbine remains directly proportional to the swept-area of the rotor, the cube of the wind speed and the density of the prevailing wind.

16.11. Yaw and Pitch Control for HAWT

The deviation angle between the longitudinal axis of a wind turbine rotor at any moment and the direction of wind stream is referred to as yaw angle. A yaw rotation is a movement around the yaw axis of an object that changes the direction the object is facing, to the left or right of its direction of motion. Yaw control is created by a mechanism incorporated with the rotor of the wind turbine, which provides a drive to allow the rotor to change direction in a horizontal plane when the wind direction changes. The main function of the yaw drive is to maximize the captured wind energy by projecting the turbine facing into the wind stream. It usually consists of one or more electric motor drive, yaw gear, gear rim and mounting bearing. Modern large wind turbines are typically actively controlled to face the wind direction measured by a wind vane (tail fin) situated on the back of the nacelle. By minimizing the yaw angle (the misalignment between wind and turbine pointing direction), the power output is maximized and non-symmetrical loads minimized. However, since the wind direction varies quickly, the turbine will not strictly follow the direction and will have a small yaw angle on average. The power output losses can simply be approximated according to cosine cube law. Particularly at low-to-medium wind speeds, yawing can make a significant reduction in turbine output, with wind direction variations of ±30° being quite common and long response times of the turbines to changes in wind direction. At high wind speeds, the wind direction is less variable. Horizontal axis wind turbines, however, need to orient their rotors into and out of the wind, which is achieved by means of passive or active yaw systems. Both passive and active systems have advantages and disadvantages and various design solutions (both active and passive) are being tried in order to find the optimal design for each wind turbine depending on its size, cost and purpose of operation.

Whenever the wind flow velocity is changing with respect to a propeller, it requires a pitch control mechanism to operate as desired. Commercial wind turbines are designed to produce optimum power at 15 m/s of wind speed. However, the wind speed always fluctuates around this optimum wind speed. To generate the optimum power, the turbine blades required to be adjusted according to the wind speed. This adjustment comes from turning the blades around their longitudinal axis referred to as pitch. When the wind speed is decreased the blade pitch is such that it exposes more surface area of the blades to the wind. Conversely, when wind speed increases the blade pitch is such that it exposes less surface area to the wind. If a blade is not designed for stall, increased wind speed will force the rotor to turn faster without a pitch control mechanism. The pitch mechanism allows the wind to flow around the blade as smoothly as possible. In order to accomplish this, the air particles are allowed to flow almost tangent to the blade rather than hitting the blade head-on. There are two kinds of pitch control mechanism. The first is called active pitch control (APC) in which case the rotor blades turn around their longitudinal axis by a computercontrolled mechanism. This type of pitch control, however, requires expensive equipment and provides effective pitch control. APC is used in one third of the large turbines currently installed. The second pitch control mechanism is called passive or stall pitch control (SPC). In this case the blade does not rotate around its longitudinal axis, but naturally creates a stall and thus lowers the rotation speed. This type, however, requires precise blade design and structurally strong towers.

The main pitch mechanism is to change the angle of attack on blades. In large wind turbine the rotation of the blades is enabled on their longitudinal axis. It can change the angle of attack of the blade with respect to the wind by which the aerodynamics characteristic of the blade can be adjusted. The pitch and yaw central system required wind speed and direction measurements respectively. The pitch control needs the wind speed to determine the angle of attack of the blade foe optimal operation. A pitch angle control mechanism controls the speed of the turbine by adjusting the pitch angle as the wind speed fluctuates. Pitch control mechanism is employed in braking a wind turbine when the wind turbine rotates at a speed higher than allowable maximum or an emergency stop of the wind turbine is required. There are two important conditions which will cause the turbine to shutdown. The first, when the wind speed exceeds the allowable maximum wind speed and the second, during an emergency. In these cases, feathering the blades, which is pitching it such that it exposes minimum surface area to the wind, will reduce torque generated by the wind to a minimum and will reduce the stress on the braking system. Adjusting the pitch angle actually adjusts the area of air contact on the rotor blades. It has found that 18 degree is the best pitch angle to get maximum rotor rotational speed.

Windmills can only extract the maximum power from the available wind when the plane of rotation of the blades is perpendicular to the direction of the wind. To ensure this the rotor mount must be free to rotate on its vertical axis and the installation must include some form of yaw control to turn the rotor into the wind. For small, lightweight installations this is normally accomplished by adding a tail fin behind the rotor in line with its axis. Any lateral component of the wind will tend to push the side of the tail fin causing the rotor mount to turn until the fin is in line with the wind. When the rotor is facing into the wind there will be no lateral force on the fin and the rotor will remain in position. Friction and inertia will tend to hold it in position so that it does not follow small disturbances. Large turbine installations have automatic control systems with wind sensors to monitor the direction of the wind and a powered mechanism to drive the rotor into its optimum position.

16.12. Location Considerations

As discussed earlier, one of the factors of prime importance in installing the wind power generator is the location. It should be installed where the wind is available in more quality for the smooth operations. Unless the proper site is utilized, wind power energy is likely to go waste. An appropriate site is one where strong wind is available all round the year; absence of hills or tall trees that create obstruction to free flow of wind and wind direction remaining same. Also significant is the speed of the wind blowing through the site which should be around 13 mph.

Generally marine locations and exposed hilltops provide the most favorable wind conditions with wind speeds consistently greater than 5 m/s. Turbulent conditions will reduce the amount of energy which can be extracted from the wind reducing in turn the overall efficiency of the system. This is more likely to be the case over land than over the sea. Raising the height of the turbine above the ground effectively lifts it above the worst of the turbulence and improves efficiency. Domestic wind turbines located between buildings in urban environments rarely operate at peak efficiency as these installations suffer from turbulence as well as being shielded from the wind by nearby buildings and trees.

Grouping 10 to 100 wind turbines together in so-called wind farms (see figure 16.14) can lead to savings of 10% to 20% in construction, distribution and maintenance costs. The required land needed to provide space for turbine towers, roads, and support structures are typically between 0.25 and 0.50 acres per turbine. With the typical capacity of the current generation of wind turbines being around 2 MW, it would take a wind farm with 2000 wind turbines covering up to 200 hectares. If it is impossible to avoid all obstacles entirely, it is advisable to use the following simple thumb rules and the situation is illustrated in figure 16.20.

1. Site the wind turbine upwind at a distance of more than two times the height of the obstruction.
2. Site the wind turbine downwind a minimum distance of 10 times, and preferably 20 times, the height of the obstruction.
3. Site the wind turbine hub at least twice the height of the obstruction above ground, if the wind turbine is immediately downwind of the obstruction.
4. The upwind and downwind directions can be defined as being aligned with the prevailing wind direction.

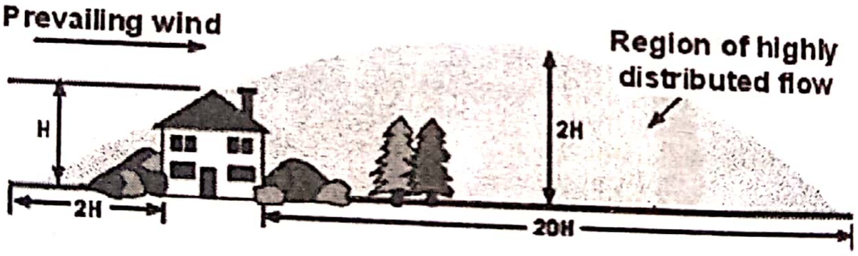


Figure 16.20: Typical Location Considerations

Wind turbines are the primary equipment necessary for wind power generation. These modern day windmills can be seen in many areas across the world. Typically painted a gray color to blend in against the sky, these towers almost always have a three-bladed fan, which is pointed into the wind by a suitable mechanism. Wind power generation via wind turbines can be used to produce ample amount of energy, and is often used in conjunction with other energy producing fuels to power cities across the country. Wind turbines can be found offshore, as well; as it is much easier to produce wind power generation using the stronger winds that come from across the waters. These winds are stronger due to the large, flat expanse of seas and oceans, which provide little or no resistance to the wind.

16.13. Small-Scale Wind Energy System

The schematic arrangement of different components of a small-scale wind turbine–generator system, generally used for domestic purpose is shown in figure 16.21. The wind turbine typically is of a simpler construction, which does not have variable pitch rotor blades so that the rotor speed varies with the wind speed. Wind turbine blade sizes in urban applications are usually limited for practical reasons to less than about 1 meter (2 meters diameter) as well as by local planning ordinances and for similar reasons the height of the turbine above ground is limited to just above rooftop level but below treetop level.

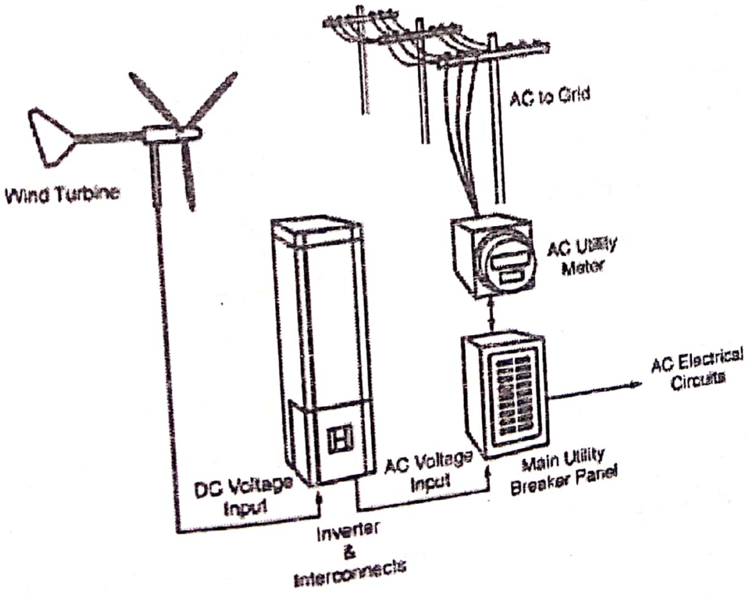


Figure 16.21: Small Scale Wind Power System

There is possible confusion in the classification of the generator. It is actually a synchronous generator because the frequency of its output is directly synchronized with the rotor speed. In this application however it is called an asynchronous generator because the output frequency of the generator is not synchronized with the mains/utility frequency. A permanent magnet asynchronous AC generator mounted on the same shaft is coupled to the wind turbine. The output voltage and frequency of the generator are therefore also dependent on the wind speed. Thus the generator output voltage and frequency are proportional to the rotor speed and the current is proportional to the torque on the shaft. In order to obtain a fixed voltage and frequency, the output from the generator is fed to a rectifier. The output is rectified and fed through a buck-boost regulator to an inverter, which generates the required fixed amplitude and frequency AC voltage.

A typical small-scale wind power system installation with a 1.75 meters rotor sweep diameter will have a swept area of 2.4 square meters. At the rated wind speed of 12.5 m/s the wind power intercepted will be 2870 Watts, but after taking into account all the unavoidable system losses, the actual electrical output power will be around 1000 Watts. However, this is at the upper end of the performance possibilities. Wind turbulence and shielding due to buildings and trees inhibits sustained strong, gust free wind flow and in any case the wind speed will more likely be towards the lower end of the performance specification at 4 m/s, that is a light breeze. At this speed the power output of the system will be about 30-40 Watts; not enough to power a single light bulb. For much of the time the power generated could be less than the quiescent power drain of the inverter. The economics of rural and remote locations make wind power more attractive than for urban locations. Because of the remoteness, connection to the electricity grid may be impossible or prohibitively expensive. Furthermore, larger, more efficient wind power installations are possible and the prevailing winds will also be higher.

14. Large-Scale Wind Energy System

A typical large-scale wind energy system that can be connected to a utility grid system is shown in figure 16.22. Large-scale wind turbine generators of up o 5 MW or more with rotor diameters of up to 120 meters are now functioning in any regions of the world. A typical system employs a fixed speed rotor, usually ith three variable pitch blades, which are controlled automatically through a speed control unit to maintain a fixed rotation speed for any wind speed. The otor drives a synchronous generator through a gearbox and the whole assembly s housed in a nacelle on top of a substantial tower with massive foundations requiring hundreds of cubic meters of reinforced concrete. Self-sufficiency and selling surplus energy back to the utility is the question that payback on the capital investment in a period of time. Because the system is connected directly o the grid there is no need for battery back up and in any case the cost of the batteries would make an already weak economic case for the system even weaker.

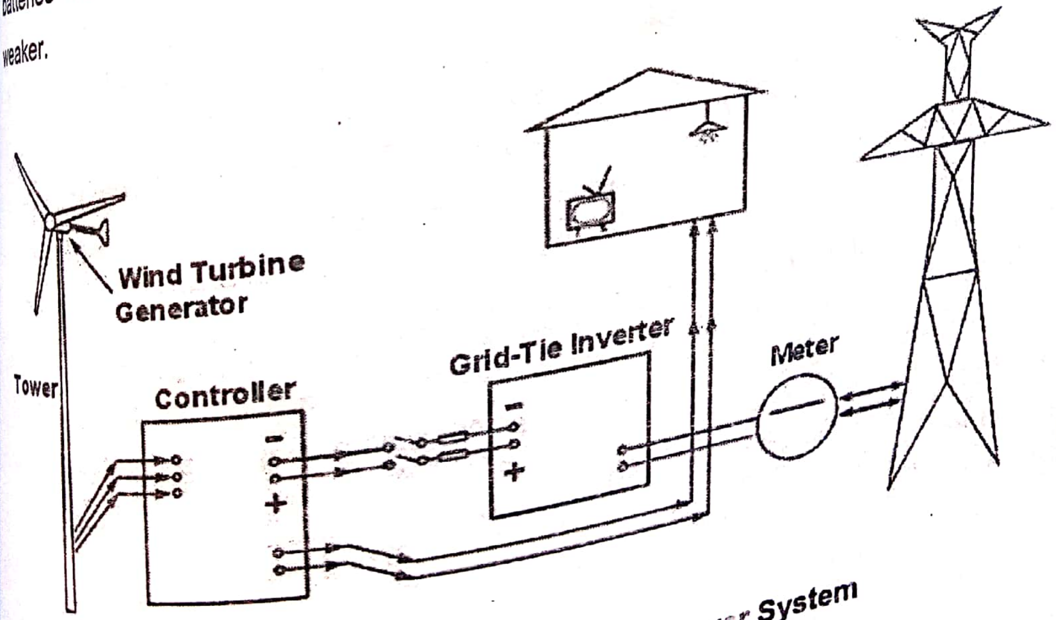


Figure 16.22: Large-Scale Wind Power System

Hybrid systems combining wind and solar power provide energy diversity, thus reducing the risk of power outages. Wind speeds are often season dependent, however, in the coastal areas of Pakistan, it is almost uniform throughout the year. On the other hand, solar energy is low in winter and high in the summer when the available solar energy is high. In addition, wind power provides a valuable complement to large-scale base load power stations. Where there is an economic back up, such as hydropower or large scale storage batteries, which can be called upon at very short notice, a significant proportion of electricity can be provided from wind turbine-generators.