UNIT II - WIND ENERGY

Power in the Wind – Types of Wind Power Plants(WPPs)–Components of WPPs-Working of WPPs- Siting of WPPs-Grid integration issues of WPPs.

Introduction

Wind power or wind energy is the use of wind to provide the mechanical power through wind turbines to operate electric generators. Wind power is a sustainable and renewable energy. Wind possesses energy by virtue of its motion. Any device capable of slowing down the mass of moving air, like a sail or propeller, can extract part of the energy and convert it into useful work. The spinning blades, attached to a hub and a low-speed shaft, turn along with the blades. The rotating low-speed shaft is connected to a gearbox that connects to a high-speed shaft on the opposite side of the gearbox. This high-speed shaft connects to an electrical generator that converts the mechanical energy from the rotation of the blades into electrical energy. The key characteristics of a good wind power site are high average wind speed, sufficient separation from noise-sensitive neighbours, good grid connection, good site access, No special environmental or landscape designations. The integration of wind into grid has certain challenges like, Variability, Uncertainty, Location-specificity, Nonsynchronous generation, Low capacity factor.

Wind Energy Basics

Wind energy is a form of solar energy. Wind is caused by the uneven heating of the atmosphere by the sun, variations in the earth's surface, and rotation of the earth. Mountains, bodies of water and vegetation influence wind flow patterns. Wind speeds vary based on geography, topography and season. As a result, there are some locations better suited for wind energy generation.

Wind power is the conversion of wind energy into electricity or mechanical energy using wind turbines. Wind turbines convert the kinetic energy in the wind into mechanical power. A generator can convert mechanical power into electricity. Mechanical power can also be utilized directly for specific tasks such as pumping water.

The mechanism used to convert air motion into electricity is referred to as a turbine. The power in the wind is extracted by allowing it to blow past moving blades that exert torque on a rotor. The rotor turns the drive shaft, which turns an electric generator. The amount of power transferred is dependent on the rotor size and the wind speed. The types of wind power plants based on capacity are

- **Utility-scale wind:** Wind turbines that range in size from 100 kilowatts to several megawatts, where the electricity is delivered to the power grid and distributed to the end user by electric utilities or power system operators.
- **Distributed or "small" wind:** Single small wind turbines below 100 kilowatts that are used to directly power a home, farm or small business and are not connected to the grid.
- **Offshore wind:** Wind turbines that are erected in large bodies of water, usually on the continental shelf. Offshore wind turbines are larger than land-based turbines and can generate more power.

Windmills: People have been using windmills for centuries to grind grain, pump water, and do other work. Windmills generate mechanical energy, but they do not generate electricity.

Wind Turbines: In contrast to windmills, modern wind turbines are highly evolved machines with more than 8,000 parts that harness wind's kinetic energy and convert it into electricity.

Wind farm: Oftentimes a large number of wind turbines are built close together, which is referred to as a wind project or wind farm. A wind farm functions as a single power plant and sends electricity to the grid.

Windmills have been in use since 2000 B.C. and were first developed in Persia and China. Ancient mariners sailed to distant lands by making use of winds. Farmers used wind power to pump water and for grinding grains. Today the most popular use of wind energy is converting it to electrical energy to meet the critical energy needs of the planet.

Power in the Wind

Wind results from the movement of air due to atmospheric pressure gradients. Wind flows from regions of higher pressure to regions of lower pressure. The larger the atmospheric pressure gradient, the higher the wind speed and thus, the greater the wind power that can be captured from the wind by means of wind energy converting machinery. The generation and movement of wind are complicated due to a number of factors. Among them, the most important factors are uneven solar heating, the Coriolis effect due to the earth's self-rotation, and local geographical conditions.

Uneven solar heating

The unevenness of the solar radiation can be attributed to four reasons.

First, the earth is a sphere revolving around the sun in the same plane as its equator. Because the surface of the earth is perpendicular to the path of the sunrays at the equator but parallel to the sunrays at the poles, the equator receives the greatest amount of energy per unit area, with energy dropping off toward the poles. Due to the spatial uneven heating on the earth, it forms a temperature gradient from the equator to the poles and a pressure gradient from the poles to the equator. Thus, hot air with lower air density at the equator rises up to the high atmosphere and moves towards the poles and cold air with higher density flows from the poles towards the equator along the earth's surface. Without considering the earth's self-rotation and the rotation-induced Coriolis force, the air circulation at each hemisphere forms a single cell, defined as the meridional circulation.

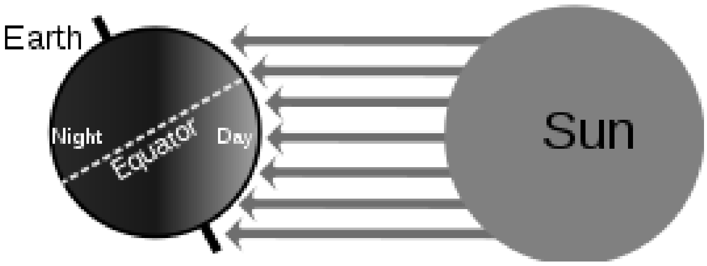


Fig. 1. Uneven solar heating

Second, the earth's self-rotating axis has a tilt of about 23.5° with respect to its ecliptic plane. It is the tilt of the earth's axis during the revolution around the sun that results in cyclic uneven heating, causing the yearly cycle of seasonal weather changes.

Third, the earth's surface is covered with different types of materials such as vegetation, rock, sand, water, ice/snow, etc., Each of these materials has different reflecting and absorbing rates to solar radiation, leading to high temperature on some areas (e.g. deserts) and low temperature on others (e.g. iced lakes), even at the same latitudes.

The fourth reason for uneven heating of solar radiation is due to the earth's topographic surface. There are a large number of mountains, valleys, hills, etc. on the earth, resulting in different solar radiation on the sunny and shady sides.

Coriolis effect

The earth's self-rotation is another important factor to affect wind direction and speed. The Coriolis force, which is generated from the earth's self-rotation, deflects the direction of atmospheric movements. In the north atmosphere wind is deflected to the right and in the south atmosphere to the left. The Coriolis force depends on the earth's latitude; it is zero at the equator and reaches maximum values at the poles. In addition, the amount of deflection on wind also depends on the wind speed; slowly blowing wind is deflected only a small amount, while stronger wind is deflected more.

In large-scale atmospheric movements, the combination of the pressure gradient due to the uneven solar radiation and the Coriolis force due to the earth's self rotation causes the single meridional cell to break up into three convectional cells in each hemisphere: the Hadley cell, the Ferrel cell, and the Polar cell as shown in Fig.2. Each cell has its own characteristic circulation pattern. In the Northern Hemisphere, the Hadley cell circulation lies between the equator and north latitude 30°, dominating tropical and sub-tropical climates. The hot air rises at the equator and flows toward the North Pole in the upper atmosphere. This moving air is deflected by Coriolis force to create the northeast trade winds. At approximately north latitude 30°, Coriolis force becomes so strong to balance the pressure gradient force. As a result, the winds are defected to the west.

The air accumulated at the upper atmosphere forms the subtropical high-pressure belt and thus sinks back to the earth's surface, splitting into two components: one returns to the equator to close the loop of the Hadley cell; another moves along the earth's surface toward North Pole to form the Ferrel Cell circulation, which lies between north latitude 30° and 60°. The air circulates towards the North Pole along the earth's surface until it collides with the cold air flowing from the North Pole at approximately north latitude 60°. Under the influence of Coriolis force, the moving air in this zone is deflected to produce westerlies. The Polar cell circulation lies between the North Pole and north latitude 60°. The cold air sinks down at the North Pole and flows along the earth's surface toward the equator. Near north latitude 60°, the Coriolis effect becomes significant to force the airflow to southwest.

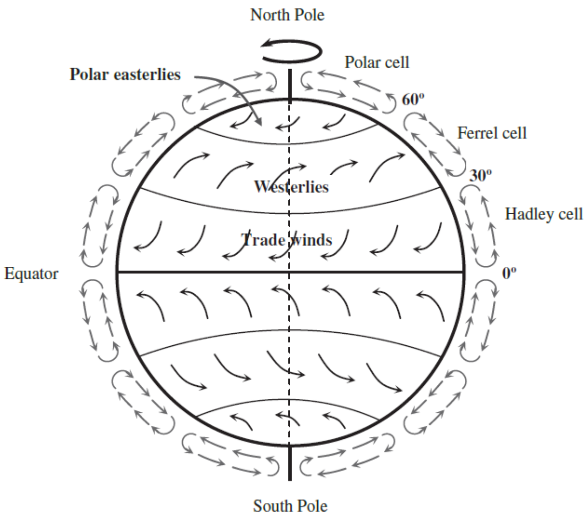


Fig. 2. Idealized atmospheric circulations

Local geography

The roughness on the earth's surface is a result of both natural geography and manmade structures. Frictional drag and obstructions near the earth's surface generally retard with wind speed and induce a phenomenon known as wind shear. The rate at which wind speed increases with height varies on the basis of local conditions of the topography, terrain, and climate, with the greatest rates of increases observed over the roughest terrain. A reliable approximation is that wind speed increases about 10% with each doubling of height. In addition, some special geographic structures can strongly enhance the wind intensity. For instance, wind that blows through mountain passes can form mountain jets with high speeds.

Wind energy characteristics

Wind energy is a special form of kinetic energy in air as it flows. Wind energy can be either converted into electrical energy by power converting machines or directly used for pumping water, sailing ships, or grinding grain. Three key factors affect the amount of energy a turbine can harness from the wind: wind speed, air density, and swept area.

Most of the modern wind turbines have 3 blades which can reach speeds at the tip of over 320 kph (200 mph).

Wind power

Kinetic energy exists whenever an object of a given mass is in motion with a translational or rotational speed. When air is in motion, the kinetic energy in moving air can be determined as

$$E_k = \frac{1}{2} m\bar{u}^2 \qquad (1)$$

where m is the air mass and $\bar{u}$ is the mean wind speed over a suitable time period. The wind power can be obtained by differentiating the kinetic energy in wind with respect to time, i.e.:

$$P_w = \frac{dE_k}{dt} = \frac{1}{2}\dot{m}\bar{u}^2 \qquad (2)$$

However, only a small portion of wind power can be converted into electrical power. When wind passes through a wind turbine and drives blades to rotate, the corresponding wind mass flowrate is

$$\dot{m} = \rho A \bar{u} \tag{3}$$

where ρ is the air density and A is the swept area of blades, as shown in Fig. 3 . Substituting (3) into (2), the available power in wind P_w can be expressed as

$$P_w = \frac{1}{2}\rho A \bar{u}^3 \tag{4}$$

An examination of eqn (4) reveals that in order to obtain a higher wind power, it requires a higher wind speed, a longer length of blades for gaining a larger swept area, and a higher air density. Because the wind power output is proportional to the cubic power of the mean wind speed, a small variation in wind speed can result in a large change in wind power.

Blade swept area

As shown in Fig. 3, the blade swept area can be calculated from the formula:

$$A = \pi\left[\left(l+r\right)^2 - r^2\right] = \pi l\,(l+2r) \tag{5}$$

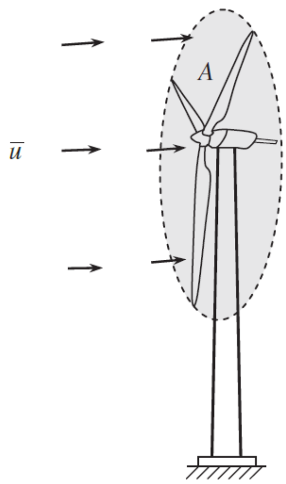


Fig.3. Swept area of wind turbine blades

where l is the length of wind blades and r is the radius of the hub. Thus, by doubling the length of wind blades, the swept area can be increased by the factor up to 4. When l >> 2 r, $A \approx \pi l^2$.

Air density

Another important parameter that directly affects the wind power generation is the density of air, which can be calculated from the equation of state:

$$\rho = \frac{p}{RT} \tag{6}$$

where p is the local air pressure, R is the gas constant (287 J/kg-K for air), and T is the local air temperature in K.

The hydrostatic equation states that whenever there is no vertical motion, the difference in pressure between two heights is caused by the mass of the air layer:

$$dp = -\rho g\, dz \tag{7}$$

where g is the acceleration of gravity. Combining eqns (6) and (7), yields

$$\frac{dp}{p} = -\frac{g}{RT}dz \tag{8}$$

The acceleration of gravity g decreases with the height above the earth's surface z:

$$g = g_0\left(1 - \frac{4z}{D}\right) \tag{9}$$

where g_0 is the acceleration of gravity at the ground and D is the diameter of the earth. However, for the acceleration of gravity g, the variation in height can be ignored because D is much larger than 4z.
In addition, temperature is inversely proportional to the height. Assume that dT /dz = c, it can be derived that

$$p = p_0 \left(\frac{T}{T_0} \right)^{-g/cR} \tag{10}$$

where p_0 and T_0 are the air pressure and temperature at the ground, respectively.
Combining eqns (6) and (10), it gives

$$\rho = \rho_0 \left(\frac{T}{T_0} \right)^{-(g/cR+1)} = \rho_0 \left(1 + \frac{cz}{T_0} \right)^{-(g/cR+1)} \tag{11}$$

This equation indicates that the density of air decreases nonlinearly with the height above the sea level.

The largest wind turbine in the world is located in US in Hawaii. It stands 20 stories tall and has blades the length of a football field.

Wind power density

Wind Power Density (WPD) is a quantitative measure of wind energy available at any location. It is the mean annual power available per square meter of swept area of a turbine, and is calculated for different heights above ground. Some of the wind resource assessments utilize 50m towers with sensors installed at intermediate levels (10 m, 20 m, etc.). For large-scale wind plants, class rating of 4 or higher is preferred. Calculation of wind power density includes the effect of wind velocity and air density.

Wind power parameters

Power coefficient

The conversion of wind energy to electrical energy involves primarily two stages: in the first stage, kinetic energy in wind is converted into mechanical energy to drive the shaft of a wind generator.
The power coefficient C_p deals with the converting efficiency in the first stage, defined as the ratio of the actually captured mechanical power by blades to the available power in wind:

$$C_p = \frac{P_{me,out}}{P_W} = \frac{P_{me,out}}{(1/2)\rho A \bar{u}^3} \tag{12}$$

Because there are various aerodynamic losses in wind turbine systems, for instance, blade-tip, blade-root, profile, and wake rotation losses, etc., the real power coefficient C_p is much lower than its theoretical limit, usually ranging from 30 to 45%.

Total power conversion coefficient and effective power output

In the second stage, mechanical energy captured by wind blades is further converted into electrical energy via wind generators. In this stage, the converting efficiency is determined by several parameters

- Gearbox efficiency η_{gear} – The power losses in a gearbox can be classified as load-dependent and no-load power losses. The load-dependent losses consist of gear tooth friction and bearing losses and no-load losses consist of oil churning, windage, and shaft seal losses. The planetary gearboxes, which are widely used in wind turbines, have higher power transmission efficiencies over traditional gearboxes.
- Generator efficiency η_{gen} – It is related to all electrical and mechanical losses in a wind generator, such as copper, iron, load, windage, friction, and other miscellaneous losses.

- Electric efficiency η_{ele} – It encompasses all combined electric power losses in the converter, switches, controls, and cables.

Therefore, the total power conversion efficiency from wind to electricity η_t is the production of these parameters, i.e.:

$$\eta_t = C_p \, \eta_{gear} \, \eta_{gen} \, \eta_{ele} \tag{13}$$

The effective power output from a wind turbine to feed into a grid becomes

$$P_{eff} = C_p \, \eta_{gear} \, \eta_{gen} \, \eta_{ele} P_W = \eta_t P_w = \frac{1}{2}\left(\eta_t \rho A \bar{u}^3\right) \tag{14}$$

Lanchester–Betz limit

The Betz limit is the theoretical maximum efficiency for a wind turbine, conjectured by German physicist Albert Betz in 1919. Betz concluded that this value is 59.3%, meaning that atmost only 59.3% of the kinetic energy from wind can be used to spin the turbine and generate electricity. In reality, turbines cannot reach the Betz limit, and common efficiencies are in the 35-45% range. If a wind turbine was 100% efficient, then all of the wind would have to stop completely upon contact with the turbine which is not practically possible.

Wind Speed – Power curve

Wind speed largely determines the amount of electricity generated by a turbine. Higher wind speeds generate more power because stronger winds allow the blades to rotate faster. Faster rotation translates to more mechanical power and more electrical power from the generator. The relationship between wind speed and power for a typical wind turbine is shown in Fig 2.

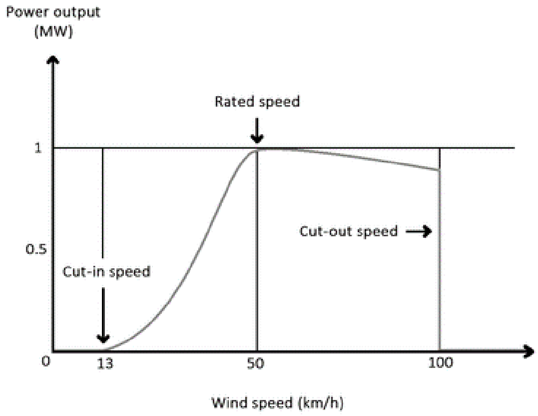


Fig.4 Wind power curve

Turbines are designed to operate within a specific range of wind speeds. The limits of the range are known as the cut-in speed and cut-out speed. The cut-in speed is the point at which the wind turbine is able to generate power. Between the cut-in speed and the rated speed, where the maximum output is reached, the power output will increase cubically with wind speed. For example, if wind speed doubles, the power output will increase 8 times. This cubic relationship is what makes wind speed such an important factor for wind power. This cubic dependence does cut out at the rated wind speed. This leads to the relatively flat part of the curve in Fig. 4, so the cubic dependence is during the speeds below 15 m/s (54 kph).

The cut-out speed is the point at which the turbine must be shut down to avoid damage to the equipment. The cut-in and cut-out speeds are related to the turbine design and size and are decided on prior to construction.

Tip Speed Ratio

The Tip Speed Ratio (often known as the TSR) is of vital importance in the design of wind turbine generators. If the rotor of the wind turbine turns too slowly, most of the wind will pass undisturbed through the gap between the rotor blades. Alternatively if the rotor turns too quickly, the blurring blades will appear like a solid wall to the wind. Therefore, wind turbines are designed with optimal tip speed ratios to extract as much power out of the wind as possible. The tip speed ratio is given by dividing the speed of the tips of the turbine blades by the speed of the wind – for example if a 20 mph wind is blowing on a wind turbine and the tips of its blades are rotating at 80 mph, then the tip speed ration is 80/20 = 4.

Force on a wind turbine

Airflow over any surface creates two types of aerodynamic forces— drag forces, in the direction of the airflow, and lift forces, perpendicular to the airflow. Either or both of these can be used to generate the forces needed to rotate the blades of a wind turbine.

Drag-based wind turbine

In drag-based wind turbines, the force of the wind pushes against a surface, like an open sail. In fact, the earliest wind turbines, dating back to ancient Persia, used this approach. The Savonius rotor is a simple drag-based windmill that you can make at home. It works because the drag of the open, or concave, face of the cylinder is greater than the drag on the closed or convex section.

Lift-based Wind Turbines

More energy can be extracted from wind using lift rather than drag, but this requires specially shaped airfoil surfaces, like those used on airplane wings. The airfoil shape is designed to create a differential pressure between the upper and lower surfaces, leading to a net force in the direction perpendicular to the wind direction. Rotors of this type must be carefully oriented (the orientation is referred to as the rotor pitch), to maintain their ability to harness the power of the wind as wind speed changes.

Types of Wind Power Plants (WPPs)

A wind power plant is simply a collection of wind turbines in one area. There are several different types of wind power plants. The following classification is based on their construction, size and usage.

Remote Wind Power Plants

Areas which are remote but are blessed with good wind speeds and frequency need a wind turbine which is maintenance free or low-maintenance for long periods of time (just imagine a service technician rushing across mountains and valleys on foot or bullock-cart to repair a turbine time and again). This means that they should have the capability of standing against all odds of climate even if they are relatively smaller in size than their conventional counterparts. These types of turbines are known as remote wind power turbines and are specifically designed with these objectives in view.

Cumulative installed capacity of wind power (as on 31.10.2019) in India is 37,090.03 MW.

Hybrid Wind Power Plants

Wind is not fully reliable so we cannot depend on wind alone for generation of power. The best bet would be to combine a wind power plant with some other renewable source of energy, like solar energy. That would be certainly a better idea and you can imagine that when there is a lot of heat, the solar generators would do their job and when the sky is overcast and winds are blowing, the wind power plants would take over. Such an arrangement is known as hybrid arrangement and is useful in regions where there is a lot of heat and wind.

Grid Connected Wind Power Plants

This concept is similar to a hybrid system. The wind power plant is used in conjunction with a main grid which supplies most of the power. The main purpose of the wind turbines is to supplement the energy supply for the grid, whereas the main function in the hybrid system is to complement the energy supply, hence the minor difference in the set up.

Wind Farms

As the name itself suggests, a wind farm is a collection of wind turbines which collectively power a given area or utility harnessing the wind force in a collective manner thereby amplifying the effect of a single unit.

These configurations are used at various locations depending on the conditions of the region and the presence of other sources of electrical supply. An optimum mix would consist of an ingenious combination of the various sources in the best possible manner.

Types of wind turbines

Wind turbines can be separated into two basic types determined by which way the turbine spins. Wind turbines that rotate around a horizontal axis are more common (like a wind mill), while vertical axis wind turbines are less frequently used (Savonius and Darrieus are the most common in the group).

1. Horizontal Axis Wind Turbines (HAWT)

Horizontal axis wind turbines (HAWT) are the common style that most of us think of a wind turbine. A HAWT has a similar design to a windmill, it has blades that look like a propeller that spin on the horizontal axis

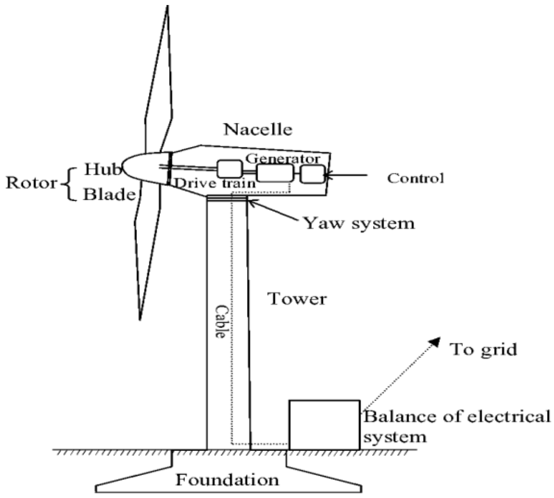


Fig. 5. Horizontal Axis Wind Turbines

Horizontal axis wind turbines have the main rotor shaft and electrical generator at the top of a tower, and they must be pointed into the wind. Small turbine are pointed by a simple wind vane placed square with the rotor (blades), while large turbines generally use a wind sensor coupled with a servo motor to turn the turbine into the wind. Most large wind turbines have a gearbox, which turns the slow rotation of the rotor into a faster rotation that is more suitable to drive an electrical generator.

Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Wind turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a small amount.

Downwind machines have been built, despite the problem of turbulence, because they don't need an additional mechanism for keeping them in line with the wind. Additionally, in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since turbulence leads to fatigue failures and reliability is so important, most HAWTs are upwind machines.

Important point to remember recording HAWT are

- Lift is the main force
- Much lower cyclic stress
- 95% of the existing turbines are HAWTs
- Nacelle is placed at the top of the tower
- Yaw mechanism is required

HAWT Advantage

- The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every ten meters up the wind speed can increase by 20% and the power output by 34%.
- High efficiency, since the blades always move perpendicular to the wind, receiving power through the whole rotation.

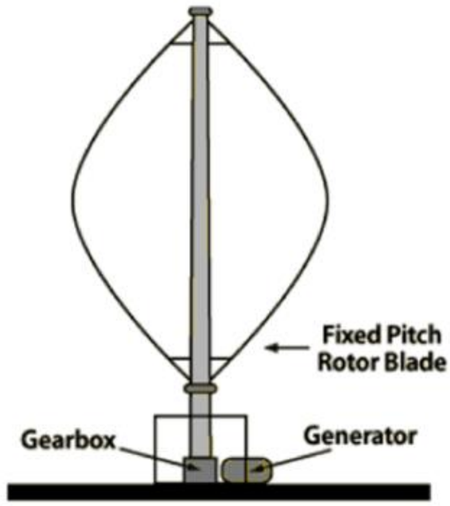
HAWT Disadvantages

- Massive tower construction is required to support the heavy blades, gearbox, and generator.
- Components of horizontal axis wind turbine (gearbox, rotor shaft and brake assembly) being lifted into position.
- Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.
- Download variants suffer from fatigue and structural failure caused by turbulence when a blade passes through the tower's wind shadow (for this reason, the majority of HAWTs use an upwind design, with the rotor facing the wind in front of the tower).
- HAWTs require an additional yaw control mechanism to turn the blades toward the wind.
- HAWTs generally require a braking or yawing device in high winds to stop the turbine from spinning and destroying or damaging itself.

2. Vertical Axis Wind Turbines (VAWT)

Vertical wind turbines (VAWTs), have the main rotor shaft arranged vertically .The main advantage of this arrangement is that the wind turbine does not need to be pointed into the wind. This makes them suitable in places where the wind direction is highly variable or has 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 issues of vibration, including noise and bearing wear which may increase the maintenance or shorten its service life. However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof and this 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.



Vertical axis

Fig. 6. Vertical Axis Wind Turbines –Darrieus type

Important points to remember for VAWT:

- Nacelle is placed at the bottom.
- Drag is the main force
- Yaw mechanism is not required
- Lower starting torque
- Difficulty in mounting the turbine
- Unwanted fluctuations in the power output

VAWT Advantages

- No yaw mechanisms is needed
- A VAWT can be located nearer the ground, making it easier to maintain the moving parts.
- VAWTs have lower wind startup speeds than the typical HAWTs.
- VAWTs may be built at locations where taller structures are prohibited.
- VAWTs situated close to the ground can take advantage of locations where rooftops, means hilltops, ridgelines, and passes funnel the wind and increase wind velocity.

VAWT Disadvantage

- In contrast to HAWT, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring airfoil surfaces to the wind leads to inherently lower efficiency.

- Most VAWTs have an average decreased efficiency from a common HAWT, mainly because of the additional drag that they have as their blades rotate into the wind. Versions that reduce drag produce more energy, especially those that funnel wind into the collector area.
- Having rotors located close to the ground where wind speeds are lower and do not take advantage of higher wind speeds above.
- Because VAWTs are not commonly deployed due mainly to the serious disadvantage mentioned above, they appear novel to those not familiar with the wind industry. This has often made them the subject of wild claims and investment scams over the last 50 years.

Tamil Nadu with 9231.77 MW of installed wind capacity is well ahead of the rest and second positioned Gujarat which has 7203.77 MW of wind generation capacity.

VAWT Subtypes

Darrieus Wind Turbine

Darrieus turbine has long, thin blades in the shape of loops connected to the top and bottom of the axle; it is often called an “eggbeater windmill” as shown in fig. 6. It is named after the French engineer Georges Darrieus who patented the design in 1931. (It was manufactured by the US company FLoWind which went bankrupt in 1997). The Darrieus turbine is characterized by its C-shaped rotor blades which give it its eggbeater appearance. It is normally built with two or three blades.

Darrieus wind turbines are commonly called “Eggbeater” turbines, because they look like a giant eggbeater. They have good efficiency, but produce large torque ripple and cyclic stress on the tower, which contributes to poor reliability. Also, they generally require some external power source, or an additional savonius rotor, to start turning, because the starting torque is very low. The torque ripple is reduced by using three or more blades which results in a higher solidity for the rotor. Solidity is measured by blade area over the rotor area. Newer Darrieus type turbines are not help up by guy-wires but have an external superstructure connected to the top bearing.

The tip speed ratio (TSR) indicates the rotating velocity of the turbines to the velocity of the wind. In this case, the TSR has a higher value than 1, meaning that the velocity rotation here is greater than the velocity of wind and generates less torque. This makes Darrieus turbines excellent electricity generators. The turbine blades have to be reinforced in order to sustain the centrifugal forces generated during rotation, but the generator itself accepts a lower amount of force than the Savorius type. A drawback to the Darrieus wind turbines is the fact that they cannot start rotation on their own. A small motor, or another Savonius turbine, maybe needed to initiate rotation.

Advantages

- The rotor shaft is vertical. Therefore it is possible to place the load, like a generator or a centrifugal pump at ground level. As the generator housing is not rotating, the cable to the load is not twisted and no brushes are requires for large twisting angles.
- The rotor can take wind from every direction.
- The visual acceptation for placing of the windmill on a building might be larger than for an horizontal axis windmill.
- Easily integrates into buildings.

Disadvantages

- Difficult start unlike the Savonius wind turbine.
- Low efficiency.

Savonius wind turbine

The Savonius wind turbine is a type of vertical-axis wind turbine. It is one of the simplest wind turbine designs. It consists of two to three “scoops” that employ a drag action to convert wind energy into torque to drive a turbine. When looked at from above in cross-section, a two scoop Savonius turbine looks like an S-shape. Due to the curvature of the scoops, the turbine encounters less drag when moving against the wind than with it, and this causes the spin in any wind regardless of facing.

Drag type wind turbines such as the Savonius turbine are less efficient at using the wind's energy than lift-type wind turbines, which are the ones commonly used in wind farms. 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 efficiency than the common HAWT. Savonius are excellent in areas of turbulent wind and self starting.

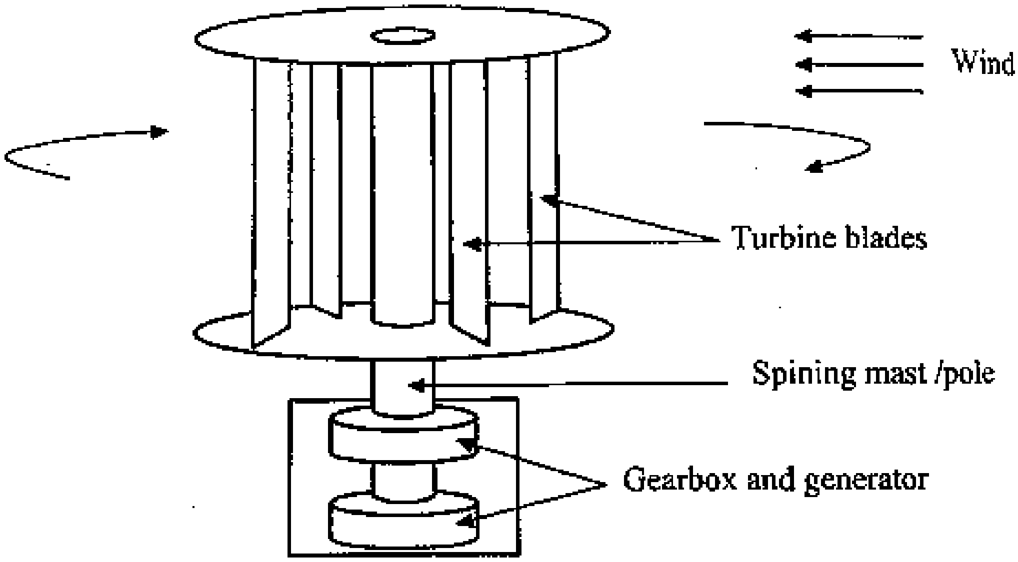


Fig. 7. Savonius wind turbine

Advantages

- Having a vertical axis, the Savonius turbine continues to work effectively even if the wind changes direction.
- Because the Savonius design works well even at low wind speeds, there's no need for a tower or other expensive structure to hold it in place, greatly reducing the initial setup cost.
- The device is quiet, easy to build, and relatively small.
- Because the turbine is close to the ground, maintenance is easy.

Disadvantages

- The scoop system used to capture the wind's energy is half as efficient as a conventional turbine, resulting in less power generation.

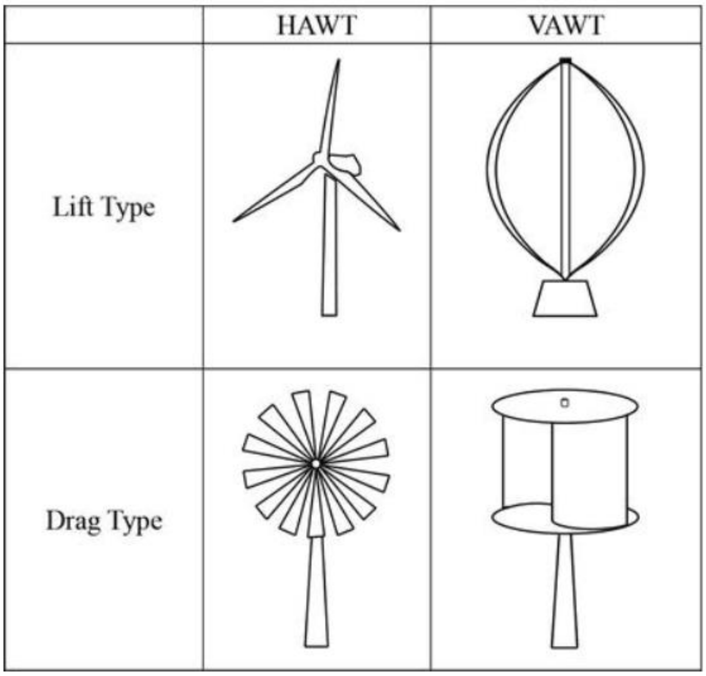


Fig.8. Types of wind turbines

Classification of Wind Energy Conversion Systems

(1) Based on axis
  - (a) Horizontal axis machines
  - (b) Vertical axis machines

(2) According to size
  - (a) Small size machines (upto 2k W)
  - (b) Medium size machines (2 to 100k W)
  - (c) Large size machines (100k W and above)
    - i. Single generator at single site
    - ii. Multiple generators

(3) Types of output
  - (a) DC output
    - i. DC generator
    - ii. Alternator rectifier
  - (b) AC output
    - i. Variable frequency, variable or constant voltage AC.
    - ii. Constant frequency, variable or constant voltage AC

(4) According to the rotational speed of the area turbines
  - (1) Constant speed and variable pitch blades
  - (2) Nearly constant speed with fixed pitch blades
  - (3) Variable speed with fixed pitch blades
    - (a) Field modulated system
    - (b) Double output indication generator
    - (c) AC-DC-AC link
    - (d) AC commentator generator
  - (4) Variable speed constant frequency generating system.

(5) As per utilization of output
  - (a) Battery storage
  - (b) Direct conversion to an electro magnetic energy converter
  - (c) Thermal potential
  - (d) Inter convention with conventional electric utility guides

> *Mupandal wind farm in Tamilnadu with 3000 turbines and total nominal power of 1,500,000 kW is India's largest* Onshore wind farm

Components of WPPs

There are three categories of components: mechanical, electrical, and control. The following is a brief description of the main components:

- **The tower** is the physical structure that holds the wind turbine. It supports the rotor, nacelle, blades, and other wind turbine equipment. Typical commercial wind towers are usually 50–120 m long and they are constructed from concrete or reinforced steel.
- **Blades** are physical structures, which are aerodynamically optimized to help capture the maximum power from the wind in normal operation with a wind speed in the range of about 3–15 m/s. Each blade is usually 20m or more in length, depending on the power level.
- **The nacelle** is the enclosure of the wind turbine generator, gearbox and internal equipment. It protects the turbine's internal components from the surrounding environment.
- **The rotor** is the rotating part of the wind turbine. It transfers the energy in the wind to the shaft. The rotor hub holds the wind turbine blades while connected to the gearbox via the low-speed shaft.
- **Pitch** is the mechanism of adjusting the angle of attack of the rotor blades. Blades are turned in their longitudinal axis to change the angle of attack according to the wind directions.
- **The shaft** is divided into two types: low and high speed. The low-speed shaft transfers mechanical energy from the rotor to the gearbox, while the high-speed shaft transfers mechanical energy from gearbox to generator.

- **Yaw** is the horizontal moving part of the turbine. It turns clockwise or anticlockwise to face the wind. The yaw has two main parts: the yaw motor and the yaw drive. The yaw drive keeps the rotor facing the wind when the wind direction varies. The yaw motor is used to move the yaw.
- **The brake** is a mechanical part connected to the high-speed shaft in order to reduce the rotational speed or stop the wind turbine over speeding or during emergency conditions.
- **Gearbox** is a mechanical component that is used to increase or decrease the rotational speed. In wind turbines, the gearbox is used to control the rotational speed of the generator.
- **The generator** is the component that converts the mechanical energy from the rotor to electrical energy. The most common electrical generators used in wind turbines are induction generators (IGs), doubly fed induction generators (DFIGs), and permanent magnet synchronous generators (PMSGs).
- **The controller** is the brain of the wind turbine. It monitors constantly the condition of the wind turbine and controls the pitch and yaw systems to extract optimum power from the wind.
- **Anemometer** is a type of sensor that is used to measure the wind speed. The wind speed information may be necessary for maximum power tracking and protection in emergency cases.
- **The wind vane** is a type of sensor that is used to measure the wind direction. The wind direction information is important for the yaw control system to operate.

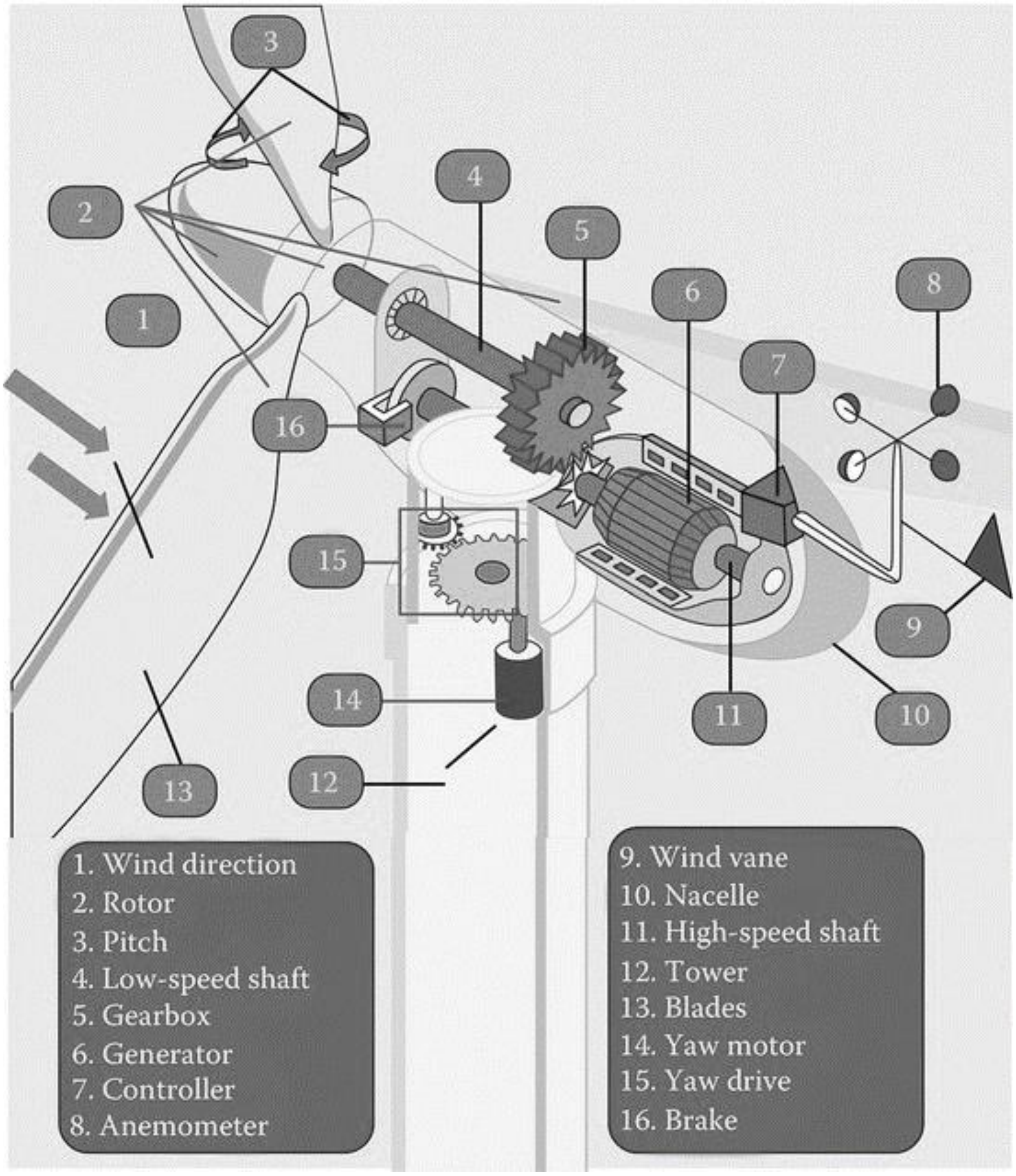


Fig. 9. Components of wind turbine

Working of WPPs (Refer Fig.10 with the following serial no)

1. Wind (moving air that contains kinetic energy) blows toward the turbine's rotor blades.
2. The rotors spin around, capturing some of the kinetic energy from the wind, and turning the central drive shaft that supports them. Although the outer edges of the rotor blades move very fast, the central axle (drive shaft) turns quite slowly.
3. In most large modern turbines, the rotor blades can swivel on the hub at the front so they meet the wind at the best angle (or "pitch") for harvesting energy. This is called the pitch control mechanism. On big turbines, small electric motors or hydraulic rams swivel the blades back and forth under precise electronic control. On smaller turbines, the pitch control is often completely mechanical. However, many turbines have fixed rotors and no pitch control at all.
4. Inside the nacelle (the main body of the turbine sitting on top of the tower and behind the blades), the gearbox converts the low-speed rotation of the drive shaft (perhaps, 16 revolutions per minute, rpm) into high-speed (perhaps, 1600 rpm) rotation fast enough to drive the generator efficiently.
5. The generator, immediately behind the gearbox, takes kinetic energy from the spinning drive shaft and turns it into electrical energy. Running at maximum capacity, a typical 2MW turbine generator will produce 2 million watts of power at about 700 volts.
6. Anemometers (automatic speed measuring devices) and wind vanes on the back of the nacelle provide measurements of the wind speed and direction.
7. Using these measurements, the entire top part of the turbine (the rotors and nacelle) can be rotated by a yaw motor, mounted between the nacelle and the tower, so it faces directly into the oncoming wind and captures the maximum amount of energy. If it is too windy or turbulent, brakes are applied to stop the rotors from turning (for safety reasons). The brakes are also applied during routine maintenance.
8. The electric current produced by the generator flows through a cable running down through the inside of the turbine tower.
9. A step-up transformer converts the electricity to about 50 times higher voltage so it can be transmitted efficiently to the power grid (or to nearby buildings or communities). If the electricity is flowing to the grid, it is converted to an even higher voltage by a substation nearby.
10. The consumer enjoy clean, green energy: the turbine has produced no greenhouse gas emissions or pollution as it operates.
11. Wind carries on blowing past the turbine, but with less speed and energy and more turbulence (since the turbine has disrupted its flow).

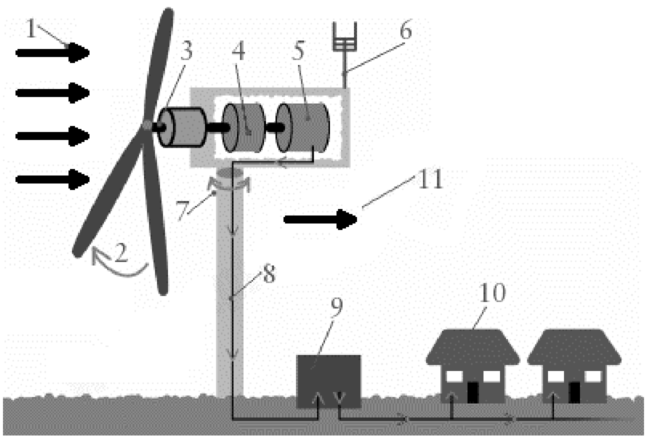


Fig. 10. Working of wind power plant

Pitch control and yaw control

Suzlon Energy Limited, Regen Powertech private limited, Inox Wind limited, Orient Green Power Limited, Vestas India, Enercon India Pvt limited, Gamesa wind turbines private limited.

Different control methods are used either to optimize or limit power output. You can control a turbine by controlling the generator speed, blade angle adjustment and rotation of the entire wind turbine. Blade angle adjustment and turbine rotation are also known as pitch and yaw control, respectively.

The purpose of **pitch control** is to maintain the optimum blade angle to achieve certain rotor speeds or power output. You can use pitch adjustment to stall and furl, two methods of pitch control. By stalling a wind turbine, you increase the angle of attack, which causes the flat side of the blade to face further into the wind. Furling decreases the angle of attack, causing the edge of the blade to face the oncoming wind. Pitch angle adjustment is the most effective way to limit output power by changing aerodynamic force on the blade at high wind speeds. This maintains the turbine's safety in the event of high winds, loss of electrical load, or other catastrophic events.

Fig. 11. Pitch control

Yaw refers to the rotation of the entire wind turbine in the horizontal axis. Yaw control ensures that the turbine is constantly facing into the wind to maximize the effective rotor area and, as a result, power. Because wind direction can vary quickly, the turbine may misalign with the oncoming wind and cause power output losses.

Fig. 12. Yaw control

Stall control

(Passive) stall controlled wind turbines have the rotor blades bolted onto the hub at a fixed angle. The geometry of the rotor blade profile, however has been aerodynamically designed to ensure that the moment the wind speed becomes too high, it creates turbulence on the side of the rotor blade which is not facing the wind. This stall prevents the lifting force of the rotor blade from acting on the rotor. In other words, as the actual wind speed in the area increases, the angle of attack of the rotor blade will increase, until at some point it starts to stall.

If you look closely at a rotor blade for a stall controlled wind turbine you will notice that the blade is twisted slightly as you move along its longitudinal axis. This is partly done in order to ensure that the rotor blade stalls gradually rather than abruptly when the wind speed reaches its critical value (other reasons for twisting the blade are mentioned in the previous section on aerodynamics).

The basic advantage of stall control is that one avoids moving parts in the rotor itself, and a complex control system. On the other hand, stall control represents a very complex aerodynamic design problem, and related design challenges in the structural dynamics of the whole wind turbine, e.g. to avoid stall-induced vibrations. Around two thirds of the wind turbines currently being installed in the world are stall controlled machines.

Siting of WPPs

The power available in the wind increases rapidly with the speed, hence wind energy conversion machines should be located preferable in areas where the winds are strong and persistent. Although daily winds at a given site may be highly variable, the monthly and especially annual average are remarkably constant from year to year.

The major contribution to the wind power available at a given site is actually made by winds with speeds above the average. Nevertheless, the most suitable sites for wind turbines would be found in areas where the annual average wind speeds are known to be moderately high or high.

The site choice for a single or a spatial array of WECS is an important matter when wind electrics is looked at from the systems point of view of aero turbine generators feeding power into a conventional electric grid.

If the WECS sites are wrongly or poorly chosen the net wind electrics generated energy per year may be sub optimal with resulting high capital cost for the WECS apparatus, high costs for wind generated electric energy, and low Returns on Investment. Even if the WECS is to be a small generator not tied to the electric grid, the siting must be carefully chosen if inordinately long break even times are to be avoided. Technical, economic, environmental, social and other factors are examined before a decision is made to erect a generating plant on a specific site. Some of the main site selection consideration are given below:

1. High annual average wind speed
2. Availability of anemometry data
3. Availability of wind V(t) Curve at the proposed site
4. Wind structure at the proposed site
5. Altitude of the proposed site
6. Terrain and its aerodynamic
7. Local Ecology
8. Distance to road or railways
9. Nearness of site to local centre/users
10. Nature of ground
11. Favourable land cost

1. **High annual average wind speed:** The speed generated by the wind mill depends on cubic values of velocity of wind, the small increases in velocity markedly affect the power in the wind. For example, Doubling the velocity, increases power by a factor of 8. It is obviously desirable to select a site for WECS with high wind velocity. Thus a high average wind velocity is the principle fundamental parameter of concern in initially appraising WESCS site. For more detailed estimate value, one would like to have the average of the velocity cubed.
2. **Availability of anemometry data:** It is another improvement sitting factor. The anemometry data should be available over some time period at the precise spot where any proposed WECS is to be built and that this should be accomplished before a sitting decision is made.
3. **Availability of wind V(t) Curve at the proposed site:** This important curve determines the maximum energy in the wind and hence is the principle initially controlling factor in predicting the electrical output and hence revenue return o the WECS machines.

   It is desirable to have average wind speed 'V' such that V>=12-16 km/hr (3.5 – 4.5 m/sec) which is about the lower limit at which present large scale WECS generators 'cut in' i.e., start turning. The V(t) Curve also determines the reliability of the delivered WECS generator power, for if the V(t) curve goes to zero there be no generated power during that time.

   If there are long periods of calm the WECS reliability will be lower than if the calm periods are short. In making such reliability estimates it is desirable to have measured V(t) Curve over about a 5 year period for the highest confidence level in the reliability estimate.
4. **Wind structure at the proposed site:** The ideal case for the WECS would be a site such that the V(t) Curve was flat, i.e., a smooth steady wind that blows all the time; but a typical site is always less than ideal. Wind specially near the ground is turbulent and gusty, and changes rapidly in direction and in velocity. This departure from homogeneous flow is collectively referred to as "the structure of the wind".
5. **Altitude of the proposed site:** It affects the air density and thus the power in the wind and hence the useful WECS electric power output. Also, as is well known, the wind tend to have higher velocities at

higher altitudes. One must be carefully to distinguish altitude from height above ground. They are not the same except for a sea level WECS site.

6. **Terrain and its aerodynamic:** One should know about terrain of the site to be chosen. If the WECS is to be placed near the top but not on the top of a not too blunt hill facing the prevailing wind, then it may be possible to obtain a 'speed-up' of the wind velocity over what it would otherwise be. Also the wind here may not flow horizontal making it necessary to tip the axis of the rotor so that the aeroturbine is always perpendicular to the actual wind flow.
   It may be possible to make use of hills or mountains which channel the prevailing wind into a pass region, thereby obtaining higher wind power.
7. **Local Ecology:** If the surface is base rock it may mean lower hub height hence lower structure cost. If trees or grass or vegetation are present, all of which tend to destructure the wind, the higher hub heights will be needed resulting in larges system costs that the bare ground case.
8. **Distance to road or railways:** This is another factor the system engineer must consider for heavy machinery, structure, materials, blades and other apparatus will have to be moved into any choosen WECS site.
9. **Nearness of site to local centre/users:** This obvious criterion minimizes transmission line length and hence losses and cost. After applying all the previous string criteria, hopefully as one narrows the proposed WECS sites to one or two they would be relatively near to the user of the generated electric energy.
10. **Nature of ground:** Ground condition should be such that the foundation for a WECS are secured. Ground surface should be stable. Erosion problem should not be there, as it could possibly later wash out the foundation of a WECS, destroying the whole system.
11. **Favourable land cost:** Land cost should be favourable as this along with other siting costs, enters into the total WECS system cost.
12. **Other conditions such as icing problem, salt spray or blowing dust should not present at the site, as they** may affect aeroturbine blades or environmental is generally adverse to machinery and electrical apparatus.

Grid integration issues of WPPs.

The electrical grid is the electrical power system network comprised of the generating plant, the transmission lines, the substation, transformers, the distribution lines and the consumer. Ideally the electric grid is aimed to operate at constant voltage and frequency. However, the grid can take some fluctuation in voltage and electrical equipment is designed for maximum and minimum allowable voltage levels, usually about +/- 10%.

Wind power generation varies depending on how wind fluctuates. However, the variations in output are smoothed when many wind power plants are aggregated over an area in a power system. To deal with uncertainty, wind power output can be forecasted minutes, hours, and even days ahead. Aggregating wind power plants over a wider geographic area will improve the forecast accuracy at all time frames.

Wind power as a generation source has specific characteristics, including variability, geographical distribution, favourable economics. Large-scale integration of both onshore and offshore wind raises challenges for the various stakeholders involved, ranging from generation, transmission and distribution to power trading and consumers.

In order to integrate wind power successfully, a number of issues need to be addressed in the following areas:

- **Variability:** Power plants that run on fuel (along with some hydro and geothermal plants) can be ramped up and down on command. They are, in the jargon, "dispatchable." But Variable Renewable Energy (VRE) plants produce power only when the wind is blowing or the sun is shining. Grid operators don't control VRE, they accommodate it, which requires some agility.
- **Uncertainty:** The output of VRE plants cannot be predicted with perfect accuracy in day-ahead and day-of forecasts, so grid operators have to keep excess reserve running just in case.
- **Location-specificity:** Sun and wind are stronger (and thus more economical) in some places than in others — and not always in places that have the necessary transmission infrastructure to get the power to where it's needed.

- **Nonsynchronous generation:** Conventional generators provide voltage support and frequency control to the grid. VRE generators can too, potentially, but it's an additional capital investment.
- **Low capacity factor:** VRE plants only run when sun or wind cooperates. According to the Energy Information Administration, in 2014 the average capacity factor — production relative to potential — for utility-scale solar PV was around 28 percent; for wind, 34 percent. (By way of comparison, the average capacity factor of US nuclear power was 92 percent; those plants are almost always producing power.) Because of the low capacity factor of VRE, conventional plants are needed to take up the slack, but because of the high output of VRE in peak hours, conventional plants sometimes don't get to run as often as needed to recover costs.
- **Design and operation of the power system:** Reserve capacities and balance management, short-term forecasting of wind power, demand side management and storage and optimisation of system flexibility;
- **Grid infrastructure issues:** Optimisation of present infrastructure, extensions and reinforcements, offshore grids and improved interconnection;
- **Grid connection of wind power:** Grid codes and power quality and wind power plant capabilities;
- **Market redesign issues:** Market aggregation and adapted market rules increase the market flexibility particularly for cross-border exchange and operating the system closer to the delivery hour;
- **Institutional issues:** Stakeholder incentives, non-discriminatory third party grid access and socialisation of costs

The cost of a single 225 KW or 250 KW which is widely preferred is about Rs. 1 Crore.

Steps to integrate wind power to grid

Despite these issues, there are solutions for integrating solar and wind into the grid

- **Improved planning and coordination:** This is the first step, making sure that VRE is matched up with appropriately flexible dispatchable plants and transmission access so that energy can be shared more fluidly within and between grid regions.
- **Flexible rules and markets:** Most grids are physically capable of more flexibility than they exhibit. Changes to the rules and markets that govern how plants are scheduled and dispatched, how reliability is assured and how customers are billed, says NREL(National Renewable Energy Laboratory), “can allow access to significant existing flexibility, often at lower economic costs than options requiring new sources of physical flexibility." This is the low-hanging fruit of grid flexibility. Recent research from the Regulatory Assistance Project offers an overview of the changes needed in "market rules, market design, and market operations." A new Department of Energy study describes utility best practices in "time-of-use pricing," which varies the price of electricity throughout the day to encourage demand shifting. In New York, utility regulations are being fundamentally rewritten to optimize the management of distributed energy resources (DERs).
- **Flexible demand and storage:** To some extent, demand can be managed like supply. "Demand response" programs aggregate customers willing to let their load be ramped up and down or shifted in time. The result is equivalent, from the grid operator's perspective, to dispatchable supply. There is a whole range of demand-management tools available and more coming online all the time. Similarly, energy storage, by absorbing excess VRE at times when it is cheap and sharing it when it is more valuable, can help even out VRE's variable supply. It can even make VRE dispatchable, within limits.
- **Flexible conventional generation:** Though older coal and nuclear plants are fairly inflexible, with extended shut-down, cool-off, and ramp-up times, lots of newer and retrofitted conventional plants are more nimble — and can be made more so by a combination of technology and improved practices. Grid planners can favor more flexible non-VRE options like natural gas and small-scale combined heat and power (CHP) plants. Cycling conventional plants up and down more often does come with a cost, but the cost is typically smaller than the fuel savings from increased VRE.

- **Flexible VRE:** New technology enables wind turbines to "provide the full spectrum of balancing services (synthetic inertial control, primary frequency control, and automatic generation control)," and both wind turbines and solar panels can now offer voltage control.
- **Interconnected transmission networks:** Wind and solar resources become less variable if aggregated across a broader region. The bigger the geographical area linked up by power lines, the more likely it is that the sun is shining or the wind is blowing somewhere within that area.

Grid Integration of wind farms and Power Quality Issues

The issue of power quality is of great importance to the wind turbines. The critical power quality issues related to integration of wind farms are discussed below.

1. **Issue of voltage variation:** If a large proportion of the grid load is supplied by wind turbines, the output variations due to wind speed changes can cause voltage variation, flicker effects in normal operation. The voltage variation can occur in specific situation, as a result of load changes, and power produce from turbine.
2. **Issue of voltage dips:** It is a sudden reduction in the voltage to a value between 1% & 90 % of the nominal value after a short period of time, conventionally 1ms to 1min. This problem is considered in the power quality and wind turbine generating system operation and computed according to the rule given in IEC 61400-3-7 standard, “Assessment of emission limit for fluctuating load”.
3. **Switching operation of wind turbine on the grid:** Switching operations of wind turbine generating system can cause voltage fluctuations and thus voltage sag, voltage swell that may cause significant voltage variation. The acceptances of switching operation depend not only on grid voltage but also on how often this may occur. The maximum number of above specified switching operation within 10-minute period and 2-hr period are defined in IEC 61400-3-7 Standard.
4. **Harmonics:** The harmonics voltage and current should be limited to acceptable level at the point of wind turbine connection in the system. This fact has lead to more stringent requirements regarding power quality, such as Standard IEC 61000-3-2 or IEEE-519.
5. **Flickers:** Flicker is the one of the important power quality aspects in wind turbine generating system. Flicker has widely been considered as a serious drawback and may limit for the maximum amount of wind power generation that can be connected to the grid. Flicker is induced by voltage fluctuations, which are caused by load flow changes in the grid. The flicker emission produced by grid-connected variable-speed wind turbines with full-scale back-to-back converters during continuous operation and mainly caused by fluctuations in the output power due to wind speed variations, the wind shear, and the tower shadow effects.
6. **Reactive power:** Traditional wind turbines are equipped with induction generators. Induction generator is preferred because they are inexpensive, rugged and requires little maintenance. Unfortunately induction generators require reactive power from the grid to operate. The interactions between wind turbine and power system network are important aspect of wind generation system.
7. **Location of wind turbine:** The way of connecting wind turbine into the electric power system highly influences the impact of the wind turbine generating system on the power quality. As a rule, the impact on power quality at the consumer’s terminal for the wind turbine generating system (WTGS) located close to the load is higher than WTGS connected away, that is connected to H.V. or EHV system.
8. **Low voltage ride through capability:** The impact of the wind generation on the power system will no longer be negligible if high penetration levels are going to be reached. The extent to which wind power can be integrated into the power system without affecting the overall stable operation depends on the technology available to mitigate the possible negative impacts such as loss of generation for frequency support, voltage flicker, voltage and power variation due to the variable speed of the wind and the risk of instability due to lower degree of controllability.
9. **IEC recommendation:** For consistent and replicable documentation of power quality characteristic of wind turbine, the international Electro-technical Commission IEC-61400-21 was developed and today, most of the large wind turbine manufactures provide power quality characteristic data accordingly. IEC 61400-21 describe the procedures for determine the power quality characteristics of wind turbines.

Grid code for wind farms

Parameter	Allowable limit
Voltage Rise	< 2%

Voltage dips	$\leq$ 3 %
Flicker	$\leq$ 0.4, for average time of 2 hours
Grid frequency	47.5-51.5 Hz