



Energy Systems

Wind Energy

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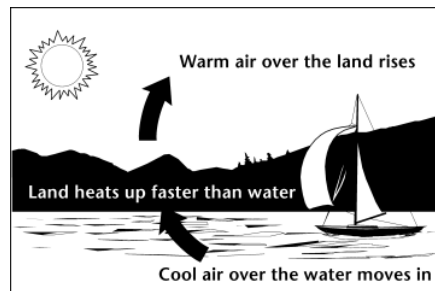
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Wind Energy

Wind is simple air in motion. It is caused by the uneven heating of the earth's surface by the sun. Since the earth's surface is made of very different types of land and water, it absorbs the sun's heat at different rates.

During the day, the air above the land heats up more quickly than the air over water. The warm air over the land expands and rises, and the heavier, cooler air rushes in to take its place, creating winds. At night, the winds are reversed because the air cools more rapidly over land than over water.



In the same way, the large atmospheric winds that circle the earth are created because the land near the earth's equator is heated more by the sun than the land near the North and South Poles.

Today, wind energy is mainly used to generate electricity. Wind is called a renewable energy source because the wind will blow as long as the sun shines.

Like old fashioned windmills, today's wind machines use blades to collect the wind's kinetic energy. Windmills work because they slow down the speed of the wind. The wind flows over the airfoil shaped blades causing lift, like the effect on airplane wings, causing them to turn. The blades are connected to a drive shaft that turns an electric generator to produce electricity.

There are two types of wind machines (turbines) used today based on the direction of the rotating shaft (axis): horizontal-axis wind machines and vertical-axis wind machines. Small turbines used to power a single home or business may have a capacity of less than 100 kilowatts. Some large commercial sized turbines may have a capacity of 5 million kilowatts, or 5 megawatts. Larger turbines are often grouped together into wind farms that provide power to the electrical grid.

BENEFITS OF WIND ENERGY

- Wind energy is an ideal renewable energy because:
 - it is a pollution-free, infinitely sustainable form of energy
 - it doesn't require fuel
 - it doesn't create greenhouse gasses

- it doesn't produce toxic or radioactive waste.
- Wind energy is quiet and does not present any significant hazard to birds or other wildlife.
- When large arrays of wind turbines are installed on farmland, only about 2% of the land area is required for the wind turbines. The rest is available for farming, livestock, and other uses.
- Landowners often receive payment for the use of their land, which enhances their income and increases the value of the land.
- Ownership of wind turbine generators by individuals and the community allows people to participate directly in the preservation of our environment.
- Each megawatt-hour of electricity that is generated by wind energy helps to reduce the 0.8 to 0.9 tonnes of greenhouse gas emissions that are produced by coal or diesel fuel generation each year.

WIND ENERGY PROGRAMME IN INDIA

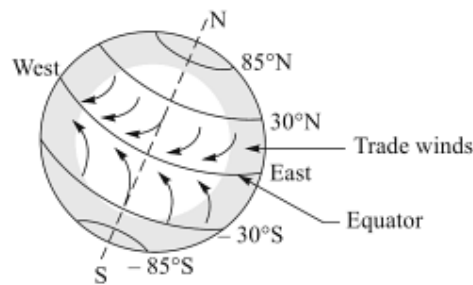
The Wind power programme in India was initiated towards the end of the Sixth Plan, in 1983-84. A market-oriented strategy was adopted from inception, which has led to the successful commercial development of the technology. The broad based National programme includes wind resource assessment activities research and development support, implementation of demonstration projects to create awareness and opening up of new sites; involvement of utilities and industry; development of infrastructure capability and capacity for manufacture installation, operation and maintenance of wind electric generators; and policy support. The programme aims at catalyzing commercialization of wind power generation in the country. The Wind Resources Assessment Programme is being implemented through the State Nodal Agencies, Field Research Unit of Indian Institute of Tropical Meteorology (IITM-FRU) and Centre for Wind Energy Technology (C-WET).

Wind resources in India are influenced by the strong south-west summer monsoon, which starts in May-June, when cool, humid air moves towards the land and the weaker north-east winter monsoon, which starts in October, when cool, dry air moves towards the ocean. During the period March to August, the winds are uniformly strong over the whole Indian Peninsula, except the eastern peninsular coast. Wind speeds during the period November to March are relatively weak, though higher winds are available during a part of the period on the Tamil Nadu coastline.

A notable feature of the Indian programme has been the interest among private investors/developers in setting up of commercial wind power projects. The gross potential is 45,000 MW (Source MNRE) and a total of a little over 7082 MW of commercial projects have been established until March 2007.

Global Winds

The primary force for global winds is produced due to differential heating of the earth surface at equator (0° longitudes) and polar regions (about ± 90° longitude). More heating takes place near the regions of equator and less heating occurs at polar regions, and so cold winds move from polar to equatorial regions. The air in touch with ocean water is much colder than air in the plain areas, and so cold winds generated from ocean areas move towards plain areas. The rotation of the earth on its axis produces Coriolis force and this force is responsible for forcing the global winds towards westernly direction. These air currents are also called trade winds as sailing ships in the past used these air currents for ship movement and trading. The global winds and circulations are shown in following figure.



Local Winds

Local winds are generated due to uneven heating. Uneven heating occurs on land surface and water bodies due to solar radiation. As a result, cool and heavy air currents move from water bodies to land surface. At night, the direction of wind is reversed as land surface cools more rapidly than water bodies. The same conditions also prevail in hilly areas where hill slope heats up during the day and cools down during the night more rapidly than the low land. This temperature difference causes air currents to move to the hill slope during the day and to the low-lying land during night.

ENERGY IN WIND

The wind has kinetic energy on account of its motion. This kinetic energy can be given by the following equation:

$$KE = P_0 = \frac{1}{2} m u_0^2$$

where m is mass of air, A = area and u₀ is speed of free air.

$$m = \rho A u_0$$

$$P_0 = \frac{1}{2} (\rho A u_0) u_0^2$$

or
$$\frac{P_0}{A} = \frac{1}{2} \rho u_0^3$$

The above relation indicates that the power available in wind per unit area is proportional to the cubic power of its speed.

ELEMENTARY FLUID FLOW CONCEPTS

Lift and Drag

The extraction of power, and hence energy, from the wind depends on creating certain forces and applying them to rotate (or to translate) a mechanism. There are two primary mechanisms for producing forces from the wind ; *lift and drag*.

By definition lift forces act perpendicular to the air flow, while drag forces act in the direction of flow. Lift forces are produced by changing the velocity of the air stream flowing over either side of the lifting surface): speeding up the air flow causes the pressure to drop, while slowing the air stream down leads to increase in pressure. In other words(any change in velocity generates a pressure difference across the lifting surface. This pressure difference produces a force that begins to act on the high pressure side and moves towards the low pressure side of the lifting surface which is called an airfoil. A good airfoil has a high lift/drag ratio, in some cases it can generate lift forces perpendicular to the air stream direction that are 30 times as great as the drag force parallel to the flow. The lift increases as the angle formed at the junction of the airfoil and the air-stream (the angle of attack) becomes less and less acute, upto the point where the angle of the air flow on the low pressure side becomes excessive. When this happens, the air flow breaks away from the low pressure side. A lot of turbulence ensues, the lift decreases and the drag increases quite substantially ; this phenomenon is known as **stalling**. (For efficient operation, a wind turbine blade needs to function with as much lift and as little drag as possible because drag dissipates energy. As lift does not involve anything more complex than deflecting the air flow, it is usually an efficient process. The design of each wind turbine specifies the angle at which the airfoil should be set to achieve the maximum lift to drag ratio.

In addition to airfoils, there are two other mechanisms for creating lift. One is the so-called **Magnus effect**, caused by spinning a cylinder in an air stream at a high-speed of rotation. The spinning slows down the air speed on the side where the cylinder is moving into wind and increases it on the other side; the result is similar to an airfoil.

The second way is to blow air through narrow slots in a cylinder, so that it emerges tangentially; this is known as a **Thwaits slot**. This also creates a rotation (or circulation) of the air flow, which in turn generates lift.

HOW WIND TURBINES WORK

Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity.

So how do wind turbines make electricity? Simply stated, a wind turbine works the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make

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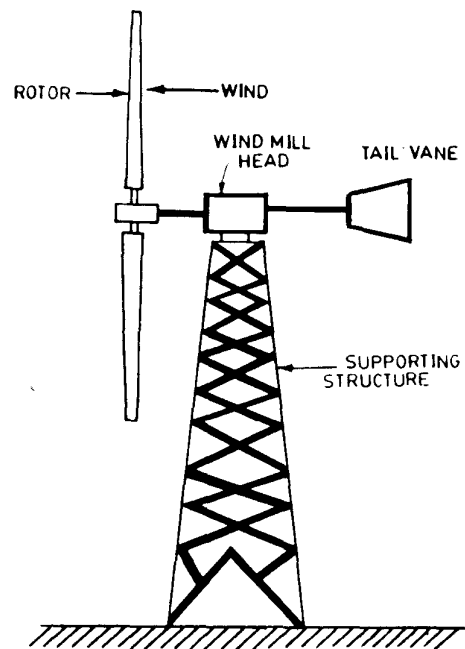
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electricity. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity. The electricity is sent through transmission and distribution lines to homes, businesses, schools, and so on.

TYPES OF WIND TURBINES

Horizontal Axis

Most wind machines being used today are the horizontal-axis type. Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable for generating electricity.



SCHMATIC OF A HORIZONTAL
AXIS TYPE WIND MILLS

Advantages of horizontal wind turbines

- Blades are to the side of the turbine's center of gravity, helping stability.
- Ability to wing warp, which gives the turbine blades the best angle of attack. Allowing the angle of attack to be remotely adjusted gives greater control, so the turbine collects the maximum amount of wind energy for the time of day and season.
- Ability to pitch the rotor blades in a storm, to minimize damage.

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- Tall tower 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%.
- Tall tower allows placement on uneven land or in offshore locations.
- Can be sited in forests above the treeline. .
- Most are self-starting.
- Can be cheaper because of higher production volume, larger sizes and, in general higher capacity factors and efficiencies.

Disadvantages of horizontal wind turbines

- HAWTs have difficulty operating in near ground, turbulent winds because their yaw and blade bearing need smoother, more laminar wind flows.
- The tall towers and long blades (up to 180 feet long) are difficult to transport on the sea and on land. Transportation can now cost 20% of equipment costs.
- Tall HAWTs are difficult to install, needing very tall and expensive cranes and skilled operators.
- Their height can be create local opposition based on impacts to viewsheds.
- Offshore tower can be a navigation problem and must be installed in shallow seas. HAWTs can't be floated on barges.
- Downwind variants suffer from fatigue and structural failure caused by turbulence.

Vertical Axis

Vertical-axis wind machines have blades that go from top to bottom and the most common type (Darrieus wind turbine) looks like a giant two-bladed egg beaters. The type of vertical wind machine typically stands 100 feet tall and 50 feet wide. Vertical-axis wind machines make up only a very small percent of the wind machines used today.

Vertical-axis wind turbines (or VAWTs) have the main rotor shaft running vertically. Key advantages of this arrangement are that the generator and/or gearbox can be placed at the bottom, near the ground, so the tower doesn't need to support it, and that the turbine doesn't need to be pointed into the wind. Drawbacks are usually the pulsating torque that can be produced during each revolution and the drag created when the blade rotates into the wind. It is also difficult to mount vertical-axis turbines on towers, meaning they must operate in the often slower, more turbulent air flow near the ground, with resulting lower energy extraction efficiency.

Advantages of vertical wind turbines

- Easier to maintain because most of their moving parts are located near the ground. This is due to the vertical wind turbine's shape. The airfoils or rotor blades are

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connected by arms to a shaft that sits on a bearing and drives a generator below, usually by first connecting to a gearbox.

- As the rotor blades are vertical, a yaw device is not needed, reducing the need for this bearing and its cost.
- Vertical wind turbines have a higher airfoil pitch angle, giving improved aerodynamics while decreasing drag at low and high pressures.
- Low height useful where laws do not permit structures to be placed high.
- Smaller VAWTs can be much easier to transport and install.
- Does not need a free standing tower so is much less expensive and stronger in high winds that are close to the ground.
- Usually have a lower Tip-Speed ratio so less likely to break in high winds.

Disadvantages of vertical wind turbines

- Most VAWTs produce energy at only 50% of the efficiency of HAWTs in large part because of the additional drag that they have as their blades rotate into the wind.
- There may be a height limitation to how tall a vertical wind turbine can be built and how much sweep area it can have.
- Most VAWTS need to be installed on a relatively flat piece of land and some sites could be too steep for them but are still usable by HAWTs.
- Most VAWT's have low starting torque.
- A VAWT that uses guyed wires to hold it in place puts stress on the bottom bearing as all the weight of the rotor is on the bearing. Guyed wires attached to the top bearing increase downward thrust in wind gusts.

TURBINES

Utility-scale turbines range in size from 100 kilowatts to as large as several megawatts. Larger turbines are grouped together into wind farms, which provide bulk power to the electrical grid.

Single small turbines, below 100 kilowatts, are used for homes, telecommunications dishes, or water pumping. Small turbines are sometimes used in connection with diesel generators, batteries, and photovoltaic systems. These systems are called hybrid wind systems and are typically used in remote, off-grid locations, where a connection to the utility grid is not available.

Savonius Wind Turbines

Savonius wind turbines are a type of *vertical-axis wind turbine* (VAWT), used for converting the power of the wind into torque on a rotating shaft. Savonius turbines are one of the simplest turbines. Aerodynamically, they are drag-type devices, consisting of two or three scoops. Looking down on the rotor from above, a two-scoop machine would look like an "S"

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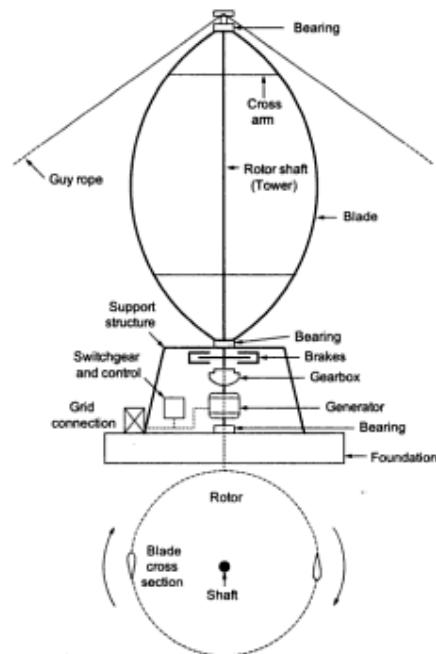
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shape in cross section. Because of the curvature, the scoops experience less drag when moving against the wind than when moving with the wind. The differential drag causes the Savonius turbine to spin. Because they are drag-type devices, Savonius turbines extract much less of the wind's power than other similarly-sized lift-type turbines. Much of the swept area of a Savonius rotor is near the ground, making the overall energy extraction less effective due to lower wind speed at lower heights.

Savonius turbines are used whenever cost or reliability is much more important than efficiency. For example, most anemometers are Savonius turbines, because efficiency is completely irrelevant for that application. Much larger Savonius turbines have been used to generate electric power on deep-water buoys, which need small amounts of power and get very little maintenance. Design is simplified because, unlike horizontal-axis turbines, no pointing mechanism is required to allow for shifting wind direction and the turbine is self-starting. Savonius and other vertical-axis machines are not usually connected to electric power grids. They can sometimes have long helical scoops, to give smooth torque.

Darrieus Wind Turbines

The constructional details of a vertical axis wind turbine (Darrieus-type rotor) are shown in following figure.



The details of the main components are as follows:

Tower (or Rotor Shaft). The tower is a hollow vertical rotor shaft, which rotates freely about the vertical axis between the top and bottom bearings. It is installed above a support structure. In the absence of any load at the top, a very strong tower is not required, which greatly simplifies its design. The upper part of the tower is supported by guy ropes. The height of the tower of a large turbine is around 100 m.

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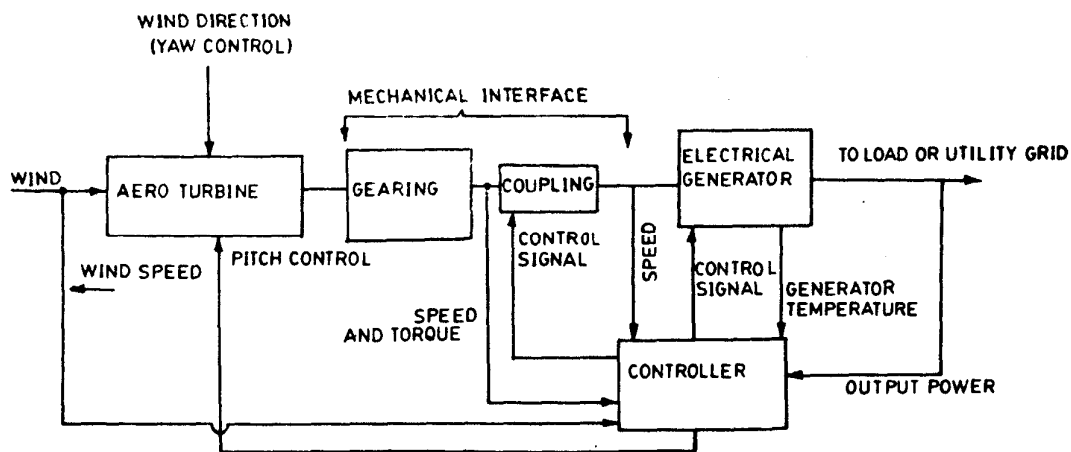
Blades. It has two or three thin, curved blades shaped like an eggbeater in a profile, with blades curved in a form that minimizes the bending stress caused by centrifugal forces—the so called Troposkein profile. The blades have an airfoil cross section with constant chord length. The pitch of the blades cannot be changed. The diameter of the rotor is slightly less than the tower height. The first large (3.8 MW), Darrieus type, Canadian machine has a rotor height as 94 m and the diameter as 65 m with a chord of 2.4 m.

Support Structure. The support structure is provided at the ground to support the weight of the rotor. Gearbox, generator, brakes, electrical switchgear and controls are housed within this structure.

Rotor. The Darrieus rotor is used for large-scale power generation. Its power coefficient is considerably better than that of an S-rotor. It runs at a large tip-speed ratio. The aerodynamic force on the blade reverses in even- revolution, causing fatigue. This, along with centrifugal force, complicates the design of the blade. One of the drawbacks of this rotor is that it is usually not self-starting. Movement may be initiated by using electrical generator as motor. As the pitch of the blade cannot change, the rotor frequency and, thus, the output power cannot be controlled. Rotor frequency increases with wind speed and power output keeps on increasing till the blades stall. Hence, at high wind speed it becomes difficult to control the output. For better performance and safety of the blades, gearbox and generator, it is desirable to limit the output to a level much below its maximum possible value.

PARTS OF TURBINE/WECS(WIND ENERGY CONVERSION SYSTEM)

The main components of a WECS are shown in following block diagram.



Following is the sketch of a wind turbine.

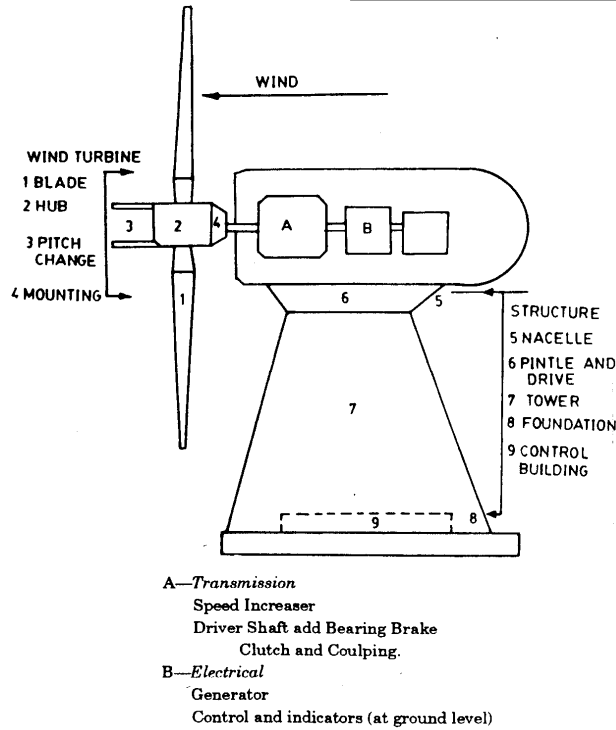


Diagram-1

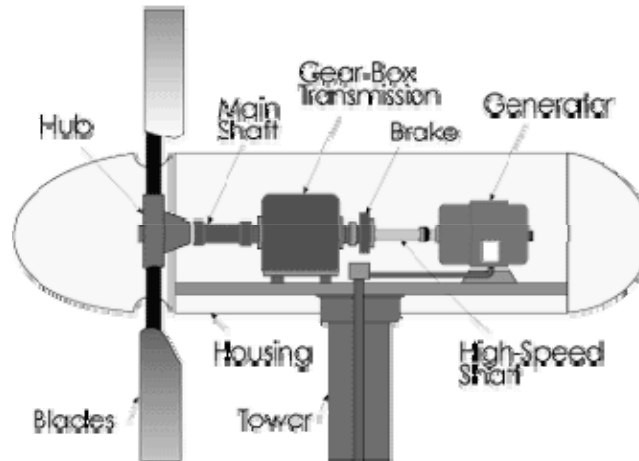


Diagram-2

The *blades* of the turbine are attached to a *hub* that is mounted on a turning *shaft*. The shaft goes through a *gear transmission box* where the turning speed is increased. The transmission is attached to a *high speed shaft* which turns a generator that makes electricity.

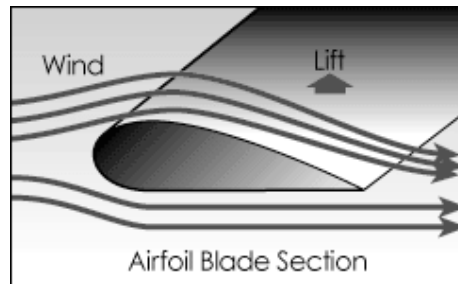
If the wind gets too high, the turbine has a *brake* that will keep the blades from turning too fast and being damaged.

Various parts are

- **Anemometer:** Measures the wind speed and transmits wind speed data to the controller.

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- **Blades:** Most turbines have either two or three blades. Wind blowing over the blades causes the blades to "lift" and rotate. The lift blade design employs the same principle that enables airplanes, kites and birds to fly.



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

- **Brake:** A disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.
- **Controller:** The controller starts up the machine at wind speeds of about 8 to 16 miles per hour (mph) and shuts off the machine at about 55 mph. Turbines do not operate at wind speeds above about 55 mph because they might be damaged by the high winds.
- **Gear box:** Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1000 to 1800 rpm, the rotational speed required by most generators to produce electricity. The gear box is a costly (and heavy) part of the wind turbine and engineers are exploring "direct-drive" generators that operate at lower rotational speeds and don't need gear boxes.
- **Generator:** The generator is what converts the turning motion of a wind turbine's blades into electricity. Inside this component, coils of wire are rotated in a magnetic field to produce electricity. Different generator designs produce either alternating current (AC) or direct current (DC), and they are available in a large range of output power ratings. The generator's rating, or size, is dependent on the length of the wind turbine's blades because more energy is captured by longer blades.

Generators that produce AC are generally equipped with features to produce the correct voltage (120 or 240 V) and constant frequency (50 Hz) of electricity, even when the wind speed is fluctuating.

DC generators are normally used in battery charging applications and for operating DC appliances and machinery. They also can be used to produce AC electricity with the use of an inverter, which converts DC to AC.

- **High-speed shaft:** Drives the generator.
- **Low-speed shaft:** The rotor turns the low-speed shaft at about 30 to 60 rotations per minute.
- **Nacelle:** The nacelle sits atop the tower and contains the gear box, low- and high-speed shafts, generator, controller, and brake. Some nacelles are large enough for a helicopter to land on.
- **Pitch:** Blades are turned, or pitched, out of the wind to control the rotor speed and keep the rotor from turning in winds that are too high or too low to produce electricity.
- **Rotor:** The portion of the wind turbine that collects energy from the wind is called the rotor. The rotor usually consists of two or more wooden, fiberglass or metal blades which rotate about an axis (horizontal or vertical) at a rate determined by the wind speed and the shape of the blades. The blades are attached to the hub, which in turn is attached to the main shaft.
- **Tower:** Towers are made from tubular steel (shown here), concrete, or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity. The tower on which a wind turbine is mounted is not just a support structure. It also raises the wind turbine so that its blades safely clear the ground and so it can reach the stronger winds at higher elevations. Maximum tower height is optional in most cases, except where zoning restrictions apply. The decision of what height tower to use will be based on the cost of taller towers versus the value of the increase in energy production resulting from their use. Studies have shown that the added cost of increasing tower height is often justified by the added power generated from the stronger winds. Larger wind turbines are usually mounted on towers ranging from 40 to 70 meters tall.
- **Wind direction:** This is an "upwind" turbine, so-called because it operates facing into the wind. Other turbines are designed to run "downwind," facing away from the wind.
- **Wind vane:** Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.
- **Yaw drive/control:** Upwind turbines face into the wind; the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines don't require a yaw drive, the wind blows the rotor downwind.
- **Yaw motor:** Powers the yaw drive.

OPERATING CHARACTERISTICS

All wind machines share certain operating characteristics, such as cut-in, rated and cut-out wind speeds.

Cut-in speed is the minimum wind speed at which the wind turbine will generate usable power. This wind speed is typically between 7 and 10 mph.

Rated Speed

The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power. For example, a "10 kilowatt" wind turbine may not generate 10 kilowatts until wind speeds reach 25 mph. Rated speed for most machines is in the range of 25 to 35 mph. At wind speeds between cut-in and rated, the power output from a wind turbine increases as the wind increases. The output of most machines levels off above the rated speed. Most manufacturers provide graphs, called "power curves," showing how their wind turbine output varies with wind speed.

Cut-out Speed

At very high wind speeds, typically between 45 and 80 mph, most wind turbines cease power generation and shut down. The wind speed at which shut down occurs is called the cut-out speed. Having a cut-out speed is a safety feature which protects the wind turbine from damage. Shut down may occur in one of several ways. In some machines an automatic brake is activated by a wind speed sensor. Some machines twist or "pitch" the blades to spill the wind. Still others use "spoilers," drag flaps mounted on the blades or the hub which are automatically activated by high rotor rpm's, or mechanically activated by a spring loaded device which turns the machine sideways to the wind stream. Normal wind turbine operation usually resumes when the wind drops back to a safe level.

WIND POWER PLANTS

Wind power plants, or wind farms as they are sometimes called, are clusters of wind machines used to produce electricity. A wind farm usually has dozens of wind machines scattered over a large area. The world's largest wind farm, the Horse Hollow Wind Energy Center in Texas, has 421 wind turbines that generate enough electricity to power 230,000 homes per year.

As a rule, wind speed increases with altitude and over open areas with no windbreaks. Good sites for wind plants are the tops of smooth, rounded hills, open plains or shorelines, and mountain gaps that produce wind funnelling.

SITE SELECTION FOR WIND TURBINE

General Comments

The ideal site is the top of a gently rounded hill rising from a flat plain covered with short grass or surrounded by water. The hilltop should have sufficient level area for all wind turbine foundations to be at the same height and the preferred soil type is sand, well bonded by short grass. Most sites fall short of this ideal and the following features should be taken into account.

Nearby obstructions or topographical features which could interfere with wind flow and/or cause excessive turbulence should be avoided. Examples of the former are trees and buildings. A good rule of thumb is to site the wind turbine a distance away from any obstruction, equal to ten times the height of that obstruction.

If a nearby obstruction upwind in the direction of the prevailing wind is unavoidable it is desirable for the hub height of the wind turbine to be 2.5 times the height of that obstruction and definitely not less than twice the height. If there is doubt on the height of tower required to raise the wind turbine above turbulent air, it is possible to get an indication of the degree of turbulence at different heights, by flying a kite in a wind speed typical of that experienced at the site.

If the site is subject to prevailing winds from one or two directions eg. regions subject to trade winds, then the prevailing wind directions are the ones which should be taken into particular account and obstacles to wind flow can be accepted in other directions.

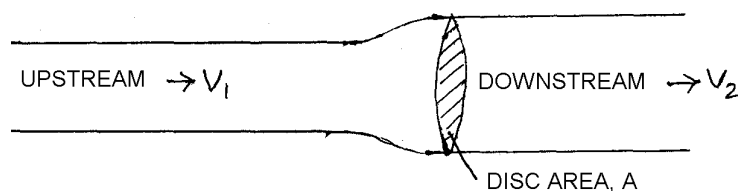
A location adjacent to steep cliffs should be avoided because they cause a high degree of turbulence. A final slope near the wind turbine of up to 1 in 3 is however acceptable

Site conditions

Sites with insufficient soil depth to allow full excavation of foundations should be avoided unless there is exposed sound rock. In this case the use of rock bolts for the guy anchors is satisfactory.

WIND TURBINE THEORY & BETZ COEFFICIENT

The simplest model is based on a momentum theory developed over a century ago. A simple representation showing the overall control volume of air is given in following figure.



Application of momentum and energy relationship shows that the effective average axial velocity at the disc, V is given by

$$V = \frac{1}{2}(V_1 + V_2) \quad (1)$$

The power output P from the disc can be expressed as the rate of extraction of kinetic energy from this flow, that is

$$P = \frac{1}{2}\rho AV(V_1^2 - V_2^2) \quad (2)$$

where ρAV is the mass flow rate through the disc.

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(ρ being air density and A the swept area of the actuator disc). It is convenient to describe the retardation in the flow using an axial inference factor a , such that

$$V = V_1(1-a) \quad (3)$$

and therefore

$$V_2 = V_1(1-2a) \quad (4)$$

Substituting V and V_2 from equations (3) and (4) into (2) so that power is expressed in terms of the upstream velocity V_1 , the power is given by

$$P = \frac{1}{2} [4a(1-a)^2] \rho A V_1^3 \quad (5)$$

The terms are grouped in this way because the $4a(1-a)^2$ term is normally known as power coefficient C_p . This is the ratio of the actual power delivered by the disc to the free stream power flowing through a similar but uninterrupted area A . If the axial interference factor “ a ” is zero then C_p is zero and no power is developed; if “ a ” is 0.5 the downstream velocity V_2 is zero.

For maximum power,

$$\frac{dP}{da} = 0$$

From equation (5), this condition leads to

$$a = 1/3$$

that is $C_{pmax} = 16/27$ (6)

Putting $a = 1/3$ in equation (4), we get

$$V_2 = \frac{1}{3} V_1 \quad (7)$$

that is for maximum power, exit velocity = one third of entrance velocity.

Hence
$$\begin{aligned} P_{max} &= \frac{1}{2} \left(\frac{16}{27} \right) (\rho A V_1^3) \\ &= 0.593 \left(\frac{1}{2} \right) (\rho A V_1^3) \\ &= 0.593 P_{total} \end{aligned} \quad (8)$$

The maximum power that can be extracted is $16/27$ times the power in wind. The fraction is known as **Betz's coefficient**. The limit is caused due to flow of fluid. The stream tube to expand downstream of actuator disc therefore free stream velocity of air must be smaller than up-stream.

The axial thrust T on the disc can also be predicted

$$T = \frac{1}{2} [4a(1-a)\rho AV_1^2] \quad (9)$$

$4a(1-a)$ is known as thrust coefficient C_T . C_T has an obvious maximum when $a = 0.5$ and the downstream velocity is zero; for maximum power output (when $a = 1/3$) C_T still has 8/9 of its maximum value.

FORCES ON BLADES AND THRUST ON TURBINE

There are two factors which act on blades

1. **Circumferential force:** acting in the direction of wheel rotation that provides the torque
2. **Axial force:** acting in the direction of the wind stream

The circumferential force, or torque T can be obtained from

$$T = P / \omega = P / \pi DN \quad (10)$$

where T = torque kgf or Newton (N); ω = angular velocity of turbine wheel, m/s; D = diameter of turbine wheel = $(\sqrt{4/A}) \cdot A$ m; N = wheel revolutions per unit time, s^{-1}

\therefore The real efficiency $\eta = P/P_{total}$

$$\text{or} \quad P = \eta \cdot P_{total} = \eta \cdot \frac{1}{2} (\rho AV_1^3) \quad (11)$$

For a turbine operating at power P, the expression for torque becomes

$$\begin{aligned} T &= \eta \cdot \frac{1}{2} (\rho AV_1^3 / \pi DN) \\ &= \eta \cdot \frac{1}{2} \cdot \frac{\rho \pi}{4} \cdot \frac{D^2 V_1^3}{\pi DN} = \eta \cdot \frac{1}{8} \cdot \frac{\rho D V_1^3}{N} = \eta \cdot \frac{1}{8} \cdot \left(\frac{\rho D V_1^3}{N} \right) \end{aligned} \quad (12)$$

At maximum efficiency ($\eta_{max} = 16/27$), the torque has maximum value T_{max} which is equal to

$$T_{max} = \frac{2}{27} \cdot \left(\frac{\rho D V_1^3}{N} \right)$$

The external force

$$F_x = \frac{1}{2} [\rho A (V_1^2 - V_2^2)] = \frac{\pi}{8} [\rho D^2 (V_1^2 - V_2^2)] \quad (13)$$

The axial force on a turbine wheel operating at maximum efficiency where $V_2 = (1/3)V_1$ is given by

$$F_{x,max} = \frac{4}{9} [\rho AV_1^2] = \frac{\pi}{9} [\rho AV_1^2] = \frac{\pi}{9} [\rho D^2 V_1^2] \quad (14)$$

Wind at 1 standard atmospheric pressure and $15^{\circ}C$ has velocity of 15 m/s, calculate

- (i) the total power density in the wind stream
- (ii) the maximum obtainable power density
- (iii) a reasonably obtainable power density
- (iv) total power
- (v) torque and axial thrust

Given: turbine diameter = 120 m, and turbine operating speed = 40 rpm at maximum efficiency. Propeller type wind turbine is considered.

Solution

For air, the value of gas constant is $R = 0.287 \text{ kJ/kg.K}$

$$1 \text{ atm} = 1.01325 \times 10^5 \text{ Pa}$$

$$\text{Air density } \rho = P/RT = (1.01325 \times 10^5)/287 \times 288 = 1.226 \text{ kg/m}^3$$

(i) Total power $P_{\text{total}} = \rho AV_1^3/2$

$$\text{Power density will be } P_{\text{total}}/A = (1/2)\rho V_1^3 = (1/2) \times 1.226 \times 15^3 = 2068.87 \text{ W/m}^2$$

(ii) Maximum power density

$$= P_{\text{max}}/A$$

$$= (8/27)\rho AV_1^3 = (8/27) \times 1.226 \times 15^3 = 1226 \text{ W/m}^2$$

(iii) Assuming efficiency = 35%

$$P/A = \eta(P_{\text{total}}/A) = 0.35 \times 2068.87 = 724 \text{ W/m}^2$$

(iv) Total power

$$P = \text{Power density} \times \text{area}$$

$$= 724 \times (\pi/4)D^2 \text{ watt}$$

$$= 8184 \text{ kW}$$

(v) Torque at maximum efficiency

$$T_{\text{max}} = (2/27)(\rho DV_1^3/N)$$

$$= (2/27)(1.226 \times 120 \times 15^3)/(40/60)$$

$$= 55170 \text{ N}$$

(vi) Maximum axial thrust

$$F_{x,\text{max}} = (\pi/9)\rho D^2 V_1^2$$

$$= (\pi/9)(1.226 \times 120^2 \times 15^2)$$

$$= 1385,870 \text{ N}$$

Wind at 1 standard atmospheric pressure and 15°C temperature has a velocity of 10 m/s. The turbine has diameter of 120 m and its operating speed is 40 rpm at maximum efficiency. Calculate

- total power density in the wind stream
- maximum obtainable power density assuming $\eta = 40\%$
- total power produced (kW)
- torque and axial thrust

Answer: 613 W/m^2 , 363 W/m^2 , 245 W/m^2 , 2270 kW , 16347 N , 616255 N

Example Q.1. (AMIE W15, 10 marks)

A wind electric generator (WEG) generates 1500 W at rated speed of 24 kmph at the atmospheric pressure and temperature of 20°C . Calculate the change in output, if the wind generator is operated at an altitude of 1800 m, temperature 10°C , wind speed 30 kmph and air pressure of 0.88 atm ($R = 287 \text{ J/kg.K}$).

Solution

Power = 1500 W; N = 24 kmph; P = atm pressure; t = 20°C

$$\rho = \frac{P}{R_t} = \frac{1.013 \times 10^5}{287(273 + 20)} = 1.205 \text{ kg/m}^3$$

Power available in wind/unit area

$$= \frac{P_0}{A_0} = \frac{1}{2} \rho u_0^3 = \frac{1}{2} \times \frac{1.205}{1} \times \left(\frac{24 \times 10^3}{60 \times 60} \right)^3 = \frac{1}{2} \times 1.205 \times 6.666^3 = 178.50 \text{ W/m}^2$$

where u_0 = velocity in m/sec.

\therefore Area in wind = $1500/178.50 = 8.40 \text{ m}^2$

Now the new data

$$\rho = \frac{P}{R_t} = \frac{0.88 \times 10^5}{283(273 + 10)} = 1.0987 \text{ kg/m}^3$$

$$\text{Power} = \frac{1}{2} \rho u_0^3$$

$$= \frac{1}{2} \times 1.0987 \times \left(\frac{30 \times 10^3}{60 \times 60} \right)^3 = 317.9 \text{ W/m}^2$$

Total power

$$= \text{power/unit area} \times \text{total area}$$

$$= 317.9 \times 8.40 = 2670 \text{ W}$$

Hence change in input = 2670 – 1500 = 1170 W

TIP SPEED RATIO

The tip-speed is the ratio of the rotational speed of the blade to the wind speed. The larger this ratio, the faster the rotation of the wind turbine rotor at a given wind speed. Electricity generation requires high rotational speeds. Lift-type wind turbines have maximum tip-speed ratios of around 10, while drag-type ratios are approximately 1. Given the high rotational speed requirements of electrical generators, it is clear that the lift-type wind turbine is most practical for this application.

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

The tip speed ratio(TSR) is given by

$$\text{TSR} = V_{\text{tip}}/V$$

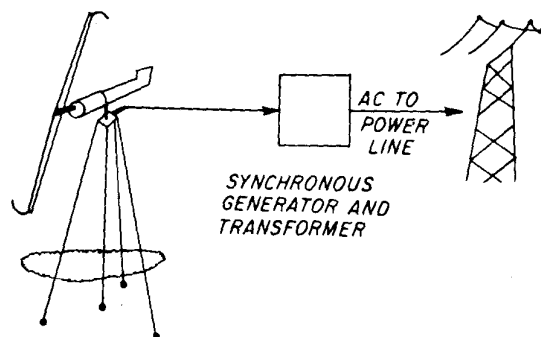
where V_{tip} = speed of the rotor tip

V = free wind speed

APPLICATIONS OF WIND ENERGY

Direct Electricity generation

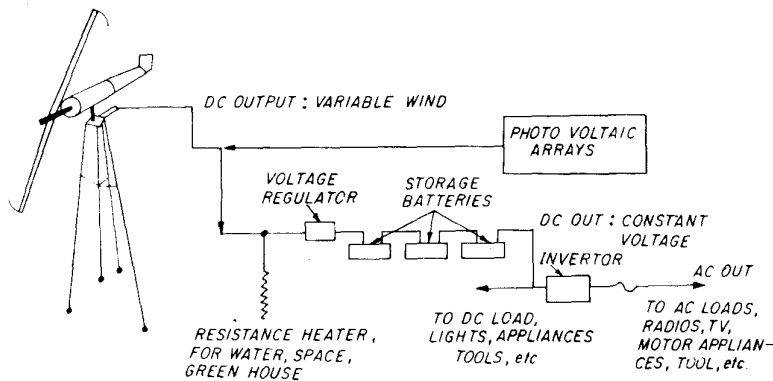
Wind power can be used in centralised utility applications to drive A.C. electrical generators. In such applications, the energy is fed directly into power networks through step-up transformers.



Electrical Storage

Batteries are the most common form of electrical storage. Where heat, rather than electricity, is the desired end product of a wind turbine application, hot water is the usual storage

medium. However, the advantageous economics of other heating systems make wind-powered heating a less attractive option.



A system with battery storage

Batteries can store and deliver only DC power. Unless an inverter is used to convert DC to AC, only DC appliances can be operated from the stored power. The battery voltage must be the same as the voltage needed to run the appliance. Standard battery voltage is 6 or 12 volts. For an appliance requiring 24 volts, two 12-volt or four 6-volt batteries connected in series are required. For a 120-volt application, you will need a series of ten 12-volt batteries.

The least costly batteries for wind applications are deep cycle, heavy-duty, industrial type lead-acid batteries, such as those used in golf carts and forklifts designed for high reliability and long life. They can be fully charged and discharged, while standard lead-acid batteries (e.g., automobile type) cannot. Gel-cell lead acid batteries have improved the safety of the traditional liquid acid battery by containing the hydrogen that can be produced during charging, and by preventing the liquid acid from spilling.

Battery conversion efficiency is approximately 60% to 80%. A battery's capacity is rated in amp-hours, a measure of its ability to deliver a certain amperage for a certain number of hours. For example, for a rating of 60 amp-hours, 3 amps can be delivered for 20 hours. Batteries should be routinely inspected for fluid level and corrosion. The storage room should be well ventilated. If allowed to accumulate, the hydrogen gas produced by some batteries can explode.

Heat Storage

When heat is the desired end product, hot water is an alternate way to store energy. It is well suited to northern climates where the heating season coincides with the windy season. There are two basic ways to produce heat from a wind turbine. Electricity can be sent to resistance heaters immersed in water, or the wind turbine's rotor shaft can be mechanically coupled to a paddle or pump that agitates water, thereby heating it.

- **Resistance Heaters.** The first method of heat storage involves electrical resistance heaters which can be DC or AC powered with unregulated voltage and frequency levels. Thus, the buyer has considerable flexibility in choosing a machine without the

need for additional complex and expensive control or conditioning devices. The conversion efficiency of a resistance heater is nearly 100%, and heat loss is minimized if the water storage tank is well-insulated. Resistance heaters can also be used directly to heat air, as with baseboard electric home heaters.

- **Mechanical Heating.** The second method of heating water is by mechanically agitating it, using either a pump or a paddle. The heat is produced by the large frictional losses that are produced by agitation. This method of heating does not require an electrical generator. Instead, the power from the rotating rotor shaft is used directly. Theoretical conversion efficiencies are nearly 100%, but practical considerations can reduce this considerably. As yet, only a few experimental models of this type of wind system have been tested.

ASSIGNMENT

- Q.1. (AMIE S14, 4 marks):** What do you know about Indian wind power generation.
- Q.2. (AMIE W11, S15, 4 marks):** What is the basic principle of wind energy conversion?
- Q.3. (AMIE S14, 8 marks):** What is Magnus effect? How this effect has been used in the development of Madaras rotor wind machine.
- Q.4. (AMIE S10, 15, 10 marks):** Describe the expression of power developed due to wind. Give classification of wind turbines on the basis of axis of rotation.
- Q.5. (AMIE W14, 10 marks):** Mathematically derive and obtain the condition of maximum output power from a wind turbine. What will be the value of maximum output power?
- Q.6. (AMIE W13, 10 marks):** List and explain various components needed for wind energy generation.
- Q.7. (AMIE W11, 10 marks):** Explain the momentum theory in wind power generation of windmill. Discuss their merits and demerits.
- Q.8. (AMIE W10, 8 marks):** Discuss Betz criterion for maximum power extraction for a wind energy turbine and explain variation of perturbation factor with power coefficient on the basis of this criterion.
- Q.9. (AMIE W10, 12, 6 marks):** Sketch the schematic diagrams of horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). Explain the functions of main components therein.
- Q.10. (AMIE W10, 10 marks):** Explain why an induction generator is preferred over d.c. generator and synchronous generator for wind energy conversion systems (WECS).
- Q.11. (AMIE W11, 6 marks):** What are the methods used to overcome the fluctuating power generation of a windmill?
- Q.12. (AMIE S11, 4 marks):** What factors led to accelerated developments of wind power? What is the range of wind speed considered favourable for wind power generation?
- Q.13. (AMIE S11, 10 marks):** What do you understand by attached and separated flow? With the help of a neat diagram, show attached and stalled flow. What are main features of stalled flow? How is the stalled performance improved?
- Q.14. (AMIE S11, 6 marks):** Discuss various types of drive schemes used in wind turbines. List their advantages and limitations.