Challenges in the Quest for Clean Energies

3. Wind Technologies

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Wind energy, like solar energy, is a renewable form of energy that can be used to generate electricity using wind turbines. There are different kinds of wind turbines and a detailed discussion of each of these is given in the article. A brief introduction to the wind energy usage in India is also given.

We have all enjoyed a nice cool breeze especially during summers. Wind is formed because of the uneven heating of the surface of earth by the sun. Heating of earth's surface and atmosphere by the sun drives convection within the atmosphere and oceans, producing winds and ocean currents. It is estimated that about 1 to 3% of the sun's energy entering the earth's atmosphere produces wind energy. The basic reason for the uneven heating is the difference in the earth's terrain, water and vegetation. For example, air above the land heats up more rapidly during the daytime than the air above water. As the air above the land, due to heating, expands and begins to move upwards, it creates a pressure difference between air on land and water. The cooler air above the water rushes in to fill the space over the land. It is this process that causes the wind to blow, as the wind is the force of air rushing to fill the low pressure area. Similarly, in the evenings, the land cools faster than water and the cool wind from over the land blows over the water.

The effects that regulate these winds are three distinctive circular wind patterns in both the Northern and Southern hemispheres – one near the equator, one at the poles and one in between. Near the equator, the heating of the land takes place rapidly because of the high direct irradiance from the sun. The hot rising air then proceeds south and north toward the poles leaving behind a low pressure area close to the earth's surface. Around the equator there is a belt of relatively low pressure known as the Doldrums.
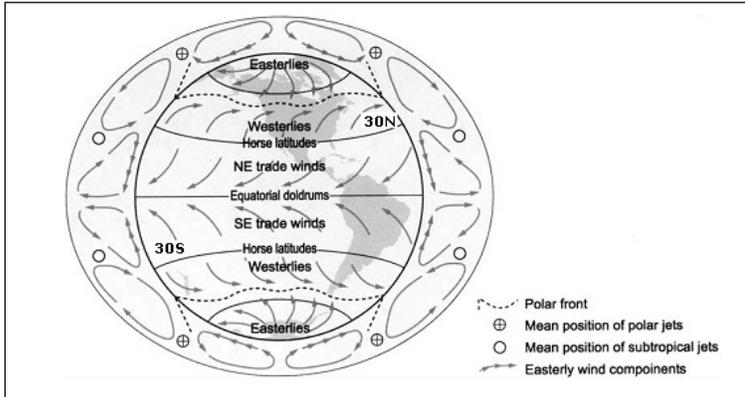
The high-altitude winds sink to the surface at around 30° latitudes in both Southern and Northern Hemispheres. Sinking winds create high-pressure zones and this, along with lots of sun, seems to be the reason for the creation of world's great deserts. Some of that sinking air heads back to the equator, which keeps the circular wind pattern going. This sets up movement of air towards the equator, from the north-east in the Northern Hemisphere and from the south-east in the Southern Hemisphere. These winds are called trade winds because they were used by sailing ships carrying goods around the world for trading. The 30° high pressure latitudes are known as horse latitudes, as shown in *Figure* 1. The movement of air results in a global wind pattern. Air moves between different areas around the world at different heights in the atmosphere. Colder air from the poles tends to sink and move towards the equator closer to the surface of the earth whereas the warm air from the equator rises and moves towards the poles high in the atmosphere because it is lighter. However, winds do not simply blow in straight lines from north to south. Instead, they are bent by the spinning of the earth to the right north of the equator and to the left in the south.

The strength of the wind depends strongly on the temperature difference, vegetative cover and terrain. The winds can be very strong, sometimes reaching speeds of 100 km/h at certain locations. Thus, there is kinetic energy associated with wind, which is also known as wind power. Usage of wind power has been around

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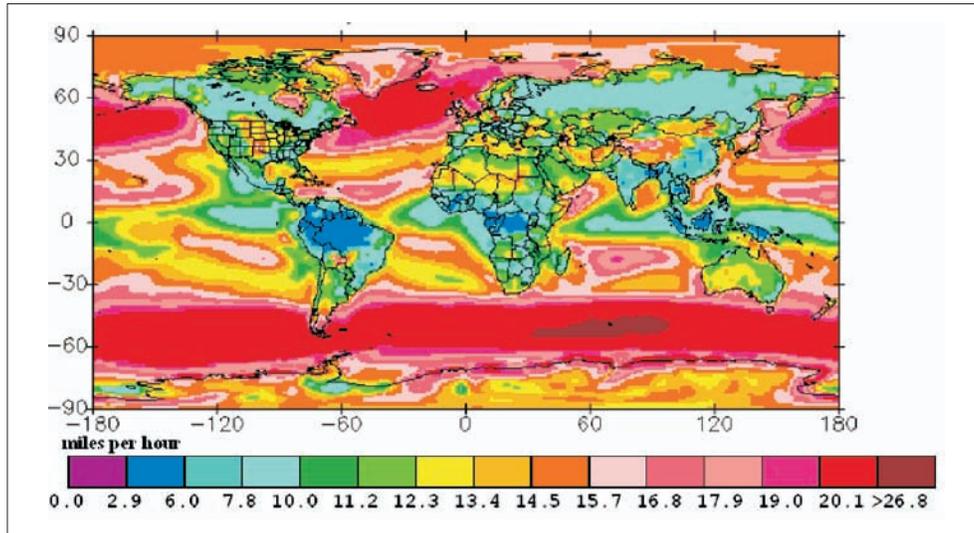
Figure 2. World wind map showing the speed of wind in different parts of the world. Reproduced with permission from http://www.climate-charts. com/World-Climate-Maps.html

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for thousands of years. The ancient Egyptians used wind power to sail boats down the Nile River. Windmills were used by the Europeans to grind wheat and other grains, and to pump water up from underground. The windmill blades would turn; this would turn a bent shaft in a circle that would move a long rod up and down from the windmill's transmission connection to the well pump's shaft. This motion pumped the water up. Then came the wind-powered generators. These are being attempted so as to reduce dependence on high priced foreign oil products to generate electricity.

Right now, most of our energy comes from burning coal and oil, which are nonrenewable resources that will eventually run out. Mining for coal and drilling for oil create large amounts of pollution, as does burning them as we saw in Part 1 of this series of articles. Wind is called a renewable energy source because it will never run out, and it is also a very clean energy source.

Principle behind the Working of the Wind Turbine

The kinetic energy of any object is the energy it possesses due to its movement. It is directly proportional to the mass of the object and the square of its velocity. Though air has a small mass it moves in the form of wind with a certain velocity and hence has

kinetic energy. The translational kinetic energy is

$$E = \left(\tfrac{1}{2}\right) mv^2, \tag{1}$$

where m is the mass of the object and v is the speed of the object moving in a straight line. In order to calculate the mass of air, the air density and volume of a certain air pocket is considered. For example, if the radius of a wind turbine is r and considering an air cylinder of length l, the mass of air hitting the wind turbine is

$$m = \rho \ (\pi r^2 l), \tag{2}$$

where ρ is the density of the air in a location. Density of air depends on factors like moisture content and hence can be season and location dependent. At sea level, the air density is known to be around 1.23 kg/m^3. If the wind velocity is v, it would cover the length l in time t; then,

$$l = v \, t. \tag{3}$$

Substituting for m and v in (1),

$$E = \left(\tfrac{1}{2}\right) (\rho \, \pi \, r^2 \, v \, t) \, v^2 \tag{4}$$
$$= K \, \rho \, r^2 \, t \, v^3, \tag{5}$$

where K is a constant comprising constants like ½ and π. The available wind power, P, which is energy imparted by wind per unit time, is

$$P = K \, \rho \, r^2 \, v^3. \tag{6}$$

Power is expressed in Watts (i.e., joules/second), the radius of the turbine in meters, the air density in kilograms per cubic meter, and the velocity in meters per second. From (6) we see that the power that can be extracted from the wind goes as velocity cubed (v^3). This means that wind blowing at 30 miles per hour has 27 times more power than one blowing at 10 miles per hour. Similarly, the power is directly proportional to the square of the radius of the wind turbine. Doubling the span that the turbine blades can sweep, increases the power by 4 times.

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According to the first law of thermodynamics the energy that is produced by the wind turbine over a certain amount of time (power) has to be equal to the energy that went into the turbine during the same period of time. The 'energy in' is the kinetic energy from the wind's velocity that flows into the area swept by the turbine blades. It is not possible to convert all of the wind's kinetic energy into mechanical energy because the turbine is not a solid disc. Some energy must remain in the air leaving the turbine. The 'energy out' is the energy converted by the turbine blades into mechanical energy (which is then converted into electricity) plus whatever energy that is left in the air after it passes through the turbine rotors. But, there is a limit, called the Betz Limit, to which the wind power can be utilized. Albert Betz, a German physicist showed in 1919 that no wind turbine can convert more than 59% of the kinetic energy of the wind into mechanical energy by turning a rotor. More details and the derivation of the limit are available elsewhere [1]. In simple terms, the power coefficient or efficiency of the turbine is,

$$C_p = P/P_{wind} \ .$$

C_p is proportional to the ratio of wind velocity behind the rotor and in front of the rotor. To extract all the energy from the wind, 100% of the wind needs to be stopped by the turbine blades which would mean that the turbine rotor will have to be a solid disc. But if the rotor is a solid disc it cannot rotate in the wind and kinetic energy will not get transferred. On the other hand, if the wind turbine had just one rotor blade, most of the wind passing through the area swept by the turbine blade would miss the blade completely and the kinetic energy would be retained by the wind. Irrespective of the rotor design, the theoretical limit for the power coefficient of a wind turbine is 0.59. In addition to this limit, due to the design aspects of the turbine, there are efficiency losses. Taking into account the inefficiencies in the generator, bearings, power transmission, etc., of the wind turbine only 10–30% of the power of the wind is actually converted into usable electricity. For example, the largest wind turbine generator in the world is located in the North Sea 15 miles off the east coast of Scotland

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near the Beatrice Oil Field (*Figure* 3). It has a rotor blade diameter of 126 meters and since it is situated at sea level, the air density is 1.23 kg/m^3. If the turbine turns at a rate of 14 meters per second (equivalent of 30 miles per hour), using (6) the power it can generate is,

$$\text{Power} = \left(\tfrac{1}{2}\right) \pi(1.23) \left(\tfrac{126}{2}\right)^2 (14)^3 = 21.04 \text{ MW}.$$

This turbine is rated for generating only 5 MW, and 21 MW of electricity can never be drawn from this wind turbine.

The kinetic energy of the wind turns the rotor blades of the wind turbine. This rotation of the blades can be converted into electrical energy using 'magnetic induction'. The principle behind this phenomenon is that if a magnet moves inside (or around) a coil of wire there is movement of charge in the wire that can be used in an external circuit.

Types of Wind Turbines

There are two main types of wind turbines determined by the way the turbine spins – about the horizontal axis or vertical axis.

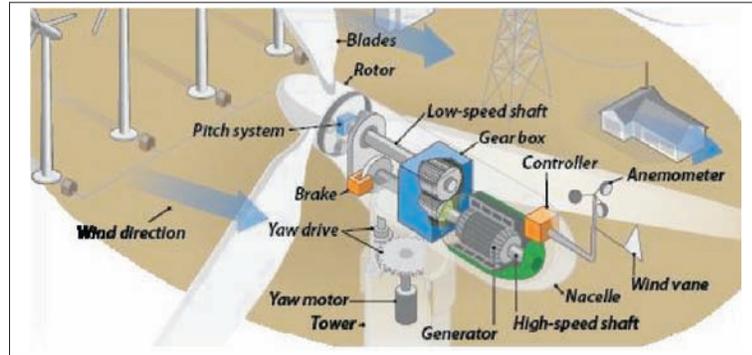### *Horizontal Axis Wind Turbine* (*HAWT*)

The HAWT is more practical and popular. A HAWT is similar to a windmill. It has blades that look like a propeller that spins on the

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Figure 4. Different parts of a HAWT that are placed on top of the tower.
Source: US DOE, Energy Efficiency and Renewable Energy, "Inside a Wind Turbine".

horizontal axis. There are two ways of positioning the HAWT, one where the wind hits the turbine blade before it hits the tower (called the horizontal upwind turbine) and the other where the wind hits the tower first (called the horizontal downwind turbine). The tower and the rotor blades are designed accordingly to withstand the wind stress.

The various parts of a horizontal wind turbine are shown in *Figure* 4. The turbine blades rotate due to the wind power, turning the shaft that is connected to them. A gearbox is attached to the tip of the shaft. It is designed such that it increases the rotation speed by a factor of more than 100 at the high-speed shaft. The high-speed shaft is connected to the generator where there is a coil of wire and a magnet. The magnet is driven by the high-speed shaft, and electric current flows in the coil that is tapped and stored.

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The nacelle is a large cover that houses the shafts, the gearbox and the generator on top of the tower. The direction of wind all through the day will not be in a single direction with a constant speed. The anemometer and wind vane fixed at the back of the nacelle provide measurements about the wind speed and direction, respectively. Using these measurements, the yaw drive and yaw motor rotate the entire top portion that includes the nacelle and the rotor blades towards the direction of the wind. The power source also comes with a safety feature. In case of extreme winds, the turbine has a break that can slow the shaft speed. This will prevent any damage to the turbine in extreme conditions.

There are other components in a HAWT. The wind turbine is placed on top of a tall tower. The higher the tower better is the wind velocity. Winds closer to the ground are not only slower but are also more turbulent. Higher winds are not disrupted by obstructions on the ground and hence are steadier. The tallest wind turbine generator is located in Laasow in Germany with the tower height of 160 meters and the rotor diameter of 90 meters. Thus, the rotor tip reaches a height of 205 meters up in the air.
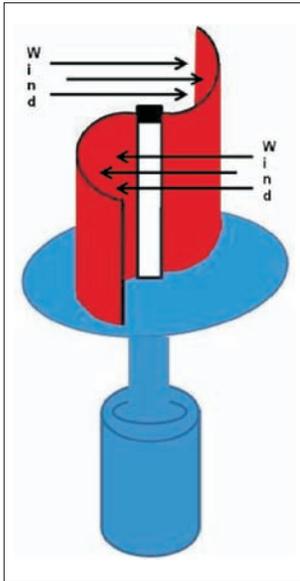
The main advantage of a HAWT is that its efficiency is high compared to other types of wind turbines because the rotor blades turn perpendicular to the wind direction receiving power throughout the whole rotation. Also, because of the tall tower structure, stronger winds can be harnessed. The disadvantage is that a massive tower construction is required to support the heavy blades, gearbox and generator. The varying wind fatigue can lead to structural failure and crack the blade roots, hub and axle of the turbines [2–4]. Also, their height makes them visible across large areas changing the landscape appearance.

Vertical Axis Wind Turbine (VAWT)

Vertical axis wind machines have blades that go from top to bottom. In VAWT the shaft connected to the blades is vertical to the ground. All of the main components like the shaft and the generator are close to the ground. Also, the wind turbine itself is near the ground, unlike horizontal wind turbines where all components are placed on a tower. The VAWT is not as efficient as the HAWT, but they do offer benefits in low wind situations. They also tend to be safer and are easier to build. They can be mounted close to the ground because they can handle turbulence well. Also the VAWTs can generate power irrespective of the wind direction and hence components like anemometer or yaw drive are not required to run them efficiently. The main disadvantage of the VAWTs is that they have lower efficiency mainly because they operate close to the ground and do not make use of the high speed winds that are present at greater heights. Just for comparison, the C_p value for a HAWT is around 0.5 while for

Figure 5. Schematic diagram of a Savonius Wind Turbine.

VAWT it is around 0.4, though most of the VAWTs average around 0.3 [5].

There are two subgroups of VAWT, namely, Savonius and Darrieus wind turbines. Savonius or S-rotor was created in 1922 by Sigurd J Savonius, a Finnish engineer. The Savonius Wind Turbine is a drag-type vertical axis wind turbine (*Figure* 5). It operates by dragging the wind, causing the rotor to be in spinning mode on the vertical axis and converting the wind's kinetic energy into usable mechanical energy. The Savonius Wind Turbine usually has about two or three cups to catch the wind. This type of wind turbine cannot rotate faster than the speed of wind. The design allows the turbine to turn relatively slowly but generate a high torque. They typically have an efficiency rating of around 15%.

Savonius wind turbines are used in electricity generation, though for small-scale domestic electricity generation, especially in locations with strong turbulent winds. The main advantage is that they continue to generate electricity in the strongest winds without being damaged; they are very quiet and are relatively easy to construct. They are self starting in the wind. They are ideally suited for the grinding of grains or pumping of water because of their higher torque factors and slower rotation.

The Darrieus Wind Turbine was designed in 1927 by a French aeronautical engineer Georges Jean Marie Darrieus. It resembles a gigantic eggbeater. It uses the lift forces generated by the wind hitting airfoils to create rotation of a set of airfoils. This turbine can spin at many times the speed of the wind hitting it. Hence a Darrieus wind turbine generates less torque than a Savonius but it rotates much faster. This makes Darrieus wind turbines much better suited to electricity generation rather than just water pumping. The centrifugal forces generated by a Darrieus turbine are very large and act on the turbine blades which therefore have to be very strong. Unlike Savonius wind turbines, Darrieus wind turbines are not self-starting. Therefore, a small powered motor is required to start the rotation and then when it has picked up

enough speed, the wind passing across the aerofoils starts to generate torque and the rotor is driven around by the wind. This type of vertical wind machine typically is about 100 feet tall and 50 feet wide (*Figure* 6).

Many modifications to the design of the VAWT have been made to suit the requirements of the urban environment. Smaller VAWT are preferred in cities because they are safer due to their lower rotational speed, can catch the wind from all directions and are silent. The helical shaped rotor blades, H-shaped straight rotor blades, Ropatec rotor blades and many other types of designs for the rotor blades are attempted. Even in the 'straight' rotor blade designs, variations in the number of blades from 2 to 4 are also attempted. Detailed aerodynamic models are built for performance prediction depending on the design of the VAWT [6,7].

Wind as Green Source of Electricity

A wind turbine converts the kinetic energy in wind into the mechanical energy of a rotating shaft. Usually this rotating mechanical energy is converted immediately by a generator into electrical energy. Advanced power electronic controls convert the electricity into the correct frequency and voltage to feed into the power grid. There are no emissions of greenhouse gases or any type of pollutants in this process of power generation. Large wind farms can be set up where high winds are known to be present. A typical installation cost of a wind farm in Europe can be in the range of 1.2 million per MW and the majority of the cost is in making the turbines as shown in *Figure* 7. The cost of electricity generated from these wind farms is in the range of
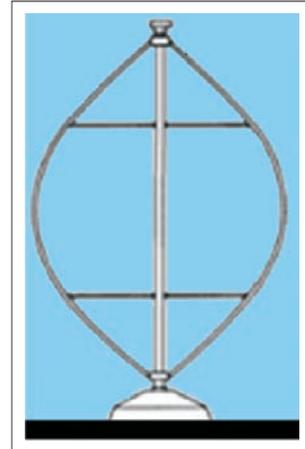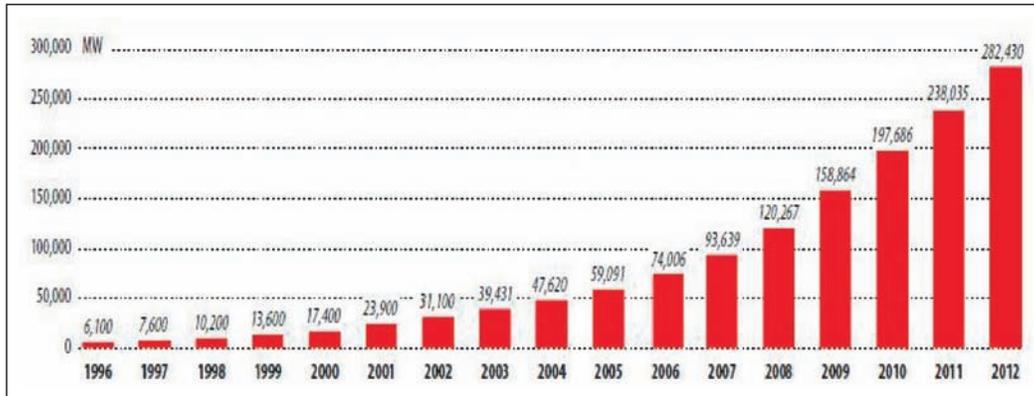

Figure 6. A Darrieus Wind Turbine.
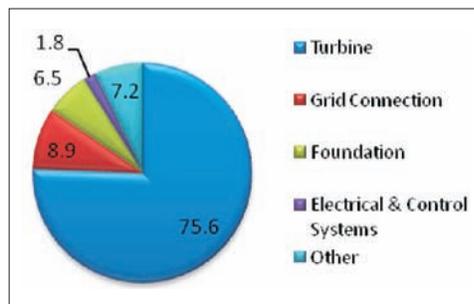
Figure 7. Share of the total cost (in percentage) of a typical 2 MW Horizontal wind turbine. Other includes land rent, paving the roads, consultancy and financial costs.

Figure 8. Global cumulative installed wind power capacity from 1996 to 2012.
Source: Danish Wind Energy Association, Global Market Statistics.

€0.12/kWh ($0.167/kWh) and 0.06/kWh ($0.09/kWh) depending on the location. Wind turbines can be built either on land or far off from land in the sea. These away-from-land wind turbine parks are called offshore installations. Cost of electricity generated from offshore wind farms is in the range of €0.17/kWh ($0.23/kWh) and 0.09/kWh ($0.12/kWh) depending again on the location.

The international wind power generation market has been growing steeply in the last 3–4 years, as seen in *Figure* 8, despite the economic slowdown. Around the world, close to 200 gigawatts of electricity is generated from wind turbines. In 2010 alone 35.8 GW wind power generation capacity was added, with Asia leading the way with the addition of 19 GW. Global Wind Energy Council (GWEC) forecasts that global wind power generation will double between 2010 and 2014, reaching close to 400 GW [8].

Europe is the leader in offshore wind generation. In 2010, Europe added 308 new offshore wind turbines, worth around 2.6 billion, generating 883 MW – a 51% increase from the previous year. As of the end of 2010 there were 1,136 offshore turbines installed that generate around 2,946 MW in 45 wind farms in nine European countries. The European Wind Energy Association (EWEA) forecasted that between 1,000 and 1,500 MW of new offshore wind capacity would be added in Europe during 2011; actually about 866 MW was added. By 2020 there would be between 40 to

55 GW of offshore wind farms, producing between 145 to 198 TWh of electricity [9].

Indian Scenario

As we saw in Part 1 of this series of articles, the Indian Government had intentions of setting up wind farms to generate 10,500 MW of electricity under the 11th Five Year Plan. In July 2012 alone, about 230 MW wind power plants were deployed, and cumulative wind power generation in the country until the end of July 2012 was close to 18,000 MW. India has the 5th largest grid connected wind power generation installation in the world after USA, Germany, China and Spain. Under the 12th Five Year Plan the target is to increase the electricity generation by 3 GW per year. By 2020, India envisages 65 GW of electricity generation from wind power saving 173 million tons of CO_2 emissions each year.

The wind power density map of India is shown in *Figure* 9, assessed for 50 m height above ground level. There are few locations where the wind power is over 200 W/sq.m. India has a potential to generate 2,900 TWh of electricity from land-based and 1,100 TWh from offshore wind farms. According to the

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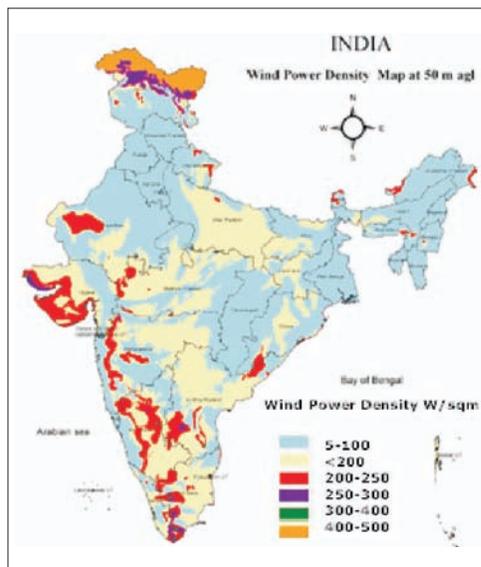
Figure 9. Wind map of India. The red, violet, green and orange regions are suitable for wind harvesting.
Source: Centre for Wind Energy Technology.

Figure 10. Wind power potential in different states of the country.
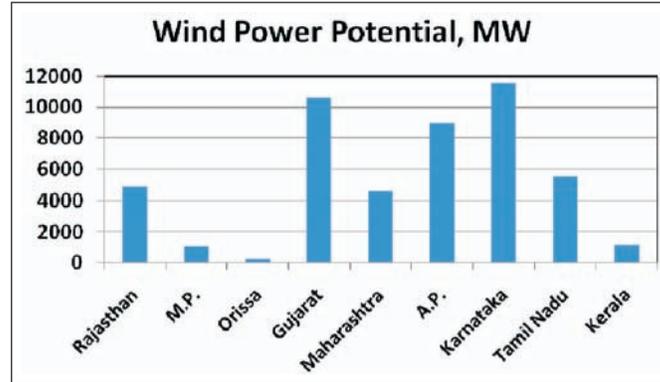
Centre for Wind Energy Technology (C-WET), based on a comprehensive wind mapping exercise, 9 states are identified that have high wind energy potential (*Figure* 10)**.** Hence wind power development is focused only in wind resource rich states, namely, Tamil Nadu, Rajasthan, Maharashtra, Gujarat, Karnataka, Kerala, Andhra Pradesh and Madhya Pradesh. The wind regime in India is influenced to a large extent by the strong monsoons starting in May–June and continuing up to October.

Though India has a long coastline, offshore wind farms have not been developed because it is a relatively new phenomenon. Also, special constructions required for setting up offshore wind power makes them 1.5– 2.5 times more expensive than land-based wind farms.

Government of India gives many financial incentives for setting up wind farms. Incentives include [10],

* Concession on import duty on specified wind turbine components
* 80% accelerated depreciation in the first year of commissioning
* 10-year income tax holiday for wind power generation projects
* Excise duty relief on wind turbine components
* Feed-in-tariff determined on cost plus basis ranging from Rs. 3.39–5.32 per kWh
* Wheeling, banking and third party sales, buy-back facility by states

Box 1. Lift and Drag Forces

When wind blows over a surface of material, because of the shape of the surface, it creates a low pressure above and high pressure area below the material surface. This pressure difference creates a lift and a drag force. The lift force is perpendicular to the wind direction and the drag force is in the wind direction. (See *Figure* A for a schematic representation). By definition,

$$\text{Lift force } F_L = \frac{1}{2}\, \rho\, A V_{rel} C_L \,,$$
$$\text{Drag force } F_D = \frac{1}{2}\, \rho\, A V_{rel} C_D \,,$$

where ρ is the density of air, A is the swept area on the foil which is the geometry factor of the blade, V_{rel} is the relative wind speed. As a first approximation V_{rel} can be imagined as the composition of the upstream wind speed V and the tangential blade element speed. C_L and C_D are the coefficients of lift and drag respectively that depend on α (see *Figure*), the angle the wind flow makes with the chord of the airfoil. α also called angle of attack.
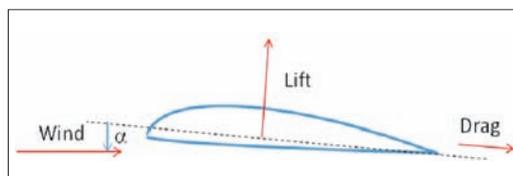
For designing a wind turbine blade, it is necessary to design the geometry and the direction in which the wind hits the blade. At very large α, the blade 'stalls' and the lift decreases. Also there is the drag force that acts like a retarding force on the blade that also increases with increasing α. There is an optimum angle 'alpha' for a particular design and contour of the blade to have maximum C_L/C_D ratio and thus have an optimum efficiency.

- Land leasing facilities are also provided for commissioning wind farms.

In India, the wind market is steadily growing. The full potential of wind power is not yet utilized in the country. With all the incentives the Indian Government is giving, the wind market is likely to grow in the near future.

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[8]   Source: Global Wind Energy Council (GWEC)

[9]   Source: European Wind Energy Association

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Suggested Reading

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