1 Introduction

1.1 What is wind turbine?

A wind turbine is a machine that converts the wind's kinetic energy into rotary mechanical energy, which is then used to do work. In more advanced models, the rotational energy is converted into electricity, the most versatile form of energy, by using a generator. If the mechanical energy is used directly by machinery, such as a pump or grinding stones, the machine is usually called a windmill. If the mechanical energy is then converted to electricity, the machine is called a wind generator, wind turbine, wind power unit (WPU), wind energy converter (WEC), or aerogenerator.

1.2 Historical Development

Windmills have been used for at least 3000 years, mainly for grinding grain or pumping water, while in sailing ships the wind has been an essential source of power for even longer. From as early as the thirteenth century, horizontal-axis windmills were an integral part of the rural economy and only fell into disuse with the advent of cheap fossil-fuelled engines and then the spread of rural electrification. The use of windmills (or wind turbines) to generate electricity can be traced back to the late nineteenth century with the 12 kW DC windmill generator constructed by Brush in the USA and the research undertaken by LaCour in Denmark. However, for much of the twentieth century there was little interest in using wind energy other than for battery charging for remote dwellings and these low-power systems were quickly replaced once access to the electricity grid became available. One notable exception was the 1250 kW Smith–Putnam wind turbine constructed in the USA in 1941. This remarkable machine had a steel rotor 53 m in diameter, full-span pitch control and flapping blades to reduce loads. Although a blade spar failed catastrophically in 1945, it remained the largest wind turbine constructed for some 40 years (Putnam, 1948).

Golding (1955) and Shepherd and Divone in Spera (1994) provide a fascinating history of early wind turbine development. They record the 100 kW 30 m diameter Balaclava wind turbine in the then USSR in 1931 and the Andrea Enfield 100 kW 24 m diameter pneumatic design constructed in the UK in the early 1950s. In this turbine hollow blades, open at the tip, were used to draw air up through the tower where another turbine drove the generator. In Denmark the 200 kW 24 m diameter Gedser machine was built in 1956 while Electricite´ de France tested a 1.1 MW 35 m diameter turbine in 1963. In Germany, Professor Hutter constructed a number of innovative, lightweight turbines in the 1950s and 1960s. In spite of these technical advances and the enthusiasm, among others, of Golding at the Electrical Research Association in the UK there was little sustained interest in wind generation until the price of oil rose dramatically in 1973.

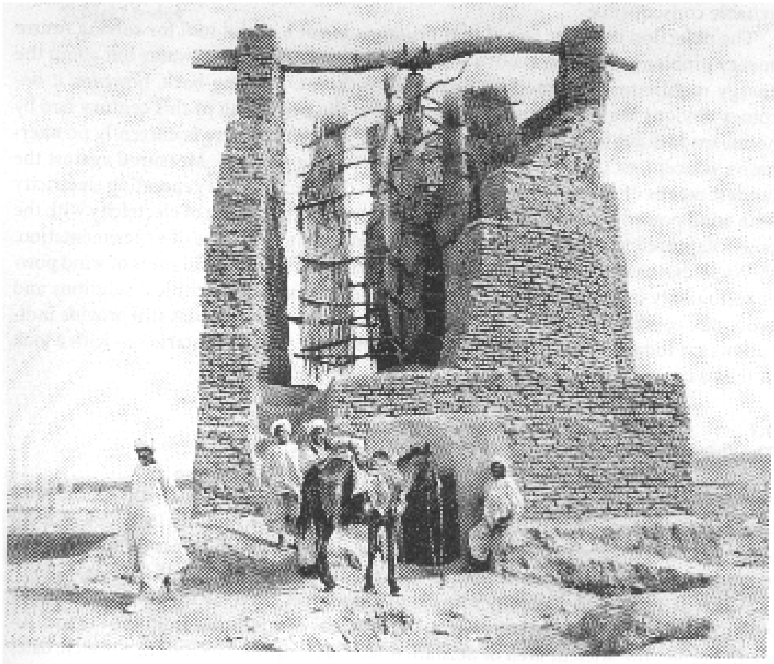


Figure 1.1: Early "WINDMILL" in Afghanistan (900AD)

The sudden increase in the price of oil stimulated a number of substantial Government-funded programmes of research, development and demonstration. In the USA this led to the construction of a series of prototype turbines starting with the 38 m diameter 100 kW Mod-0 in 1975 and culminating in the 97.5 m diameter 2.5 MW Mod-5B in 1987. Similar programmes were pursued in the UK, Germany and Sweden. There was considerable uncertainty as to which architecture might prove most cost-effective and several innovative concepts were investigated at full scale. In Canada, a 4 MW vertical-axis Darrieus wind turbine was constructed and this concept was also investigated in the 34 m diameter Sandia Vertical Axis Test Facility in the USA. In the UK, an alternative vertical-axis design using straight blades to give an 'H' type rotor was proposed by Dr Peter Musgrove and a 500 kW prototype constructed. In 1981 an innovative horizontal-axis 3 MW wind turbine was built and tested in the USA. This used hydraulic transmission and, as an alternative to a yaw drive, the entire structure was orientated into the wind. The best choice for the number of blades remained unclear for some while and large turbines were constructed with one, two or three blades. Much important scientific and engineering information was gained from these Government-funded research programmes and the prototypes generally worked as designed. However, it has to be recognized that the problems of operating very large wind turbines, unmanned and in difficult wind climates were often under- estimated and the reliability of the prototypes was not good. At the same time as the multi-megawatt prototypes were being constructed private companies, often with considerable state support, were constructing much smaller, often simpler, turbines for commercial sale. In particular the financial support mechanisms in California in the mid-1980s resulted in the installation of a very large number of quite small (, 100 kW) wind turbines.

A number of these designs also suffered from various problems but, being smaller, they were in general easier to repair and modify. The so-called 'Danish' wind turbine concept emerged of a three-bladed, stall-regulated rotor and a fixed-speed, induction machine drive train. This deceptively simple architecture has proved to be remarkably successful and has now been implemented on turbines as large as 60 m in diameter and at ratings of 1.5 MW. The machines of Figures 1.1 and 1.2 are examples of this design. However, as the sizes of commercially available turbines now approach that of the large prototypes of the 1980s it is interesting to see that the concepts investigated then of variable-speed operation, full-span control of the blades, and advanced materials are being used increasingly by designers. Figure 1.3 shows a wind farm of direct-drive, variable speed wind turbines. In this design, the synchronous generator is coupled directly to the aerodynamic rotor so eliminating the requirement for a gearbox. Figure 1.4 shows a more conventional, variable-speed wind turbine that uses a gearbox, while a small wind farm of pitch-regulated wind turbines, where full-span control of the blades is used to regulate power, is shown in Figure 1.5.

Figure 1.2: 750 kW, 48 m diameter Wind Turbine, Denmark (Reproduced by permission of NEG MICON)

Figure 1.3: Wind Farm of Variable-Speed Wind Turbines in Complex Terrain (Reproduced by permission of Wind Prospect Ltd.)

Figure 1.4: 1 MW Wind Turbine in Northern Ireland (Reproduced by permission of Renewable Energy Systems Ltd.)

The stimulus for the development of wind energy in 1973 was the price of oil and concern over limited fossil-fuel resources. Now, of course, the main driver for use of wind turbines to generate electrical power is the very low CO2 emissions (over the entire life cycle of manufacture, installation, operation and de-commissioning) and the potential of wind energy to help limit climate change. In 1997 the Commission of the European Union published its White Paper (CEU, 1997) calling for 12 percent of the gross energy demand of the European Union to be contributed from renewable by 2010. Wind energy was identified as having a key role to play in the supply of renewable energy with an increase in installed wind turbine capacity from 2.5 GW in 1995 to 40 GW by 2010. This target is likely to be achievable since at the time of writing, January 2001, there was some 12 GW of installed wind-turbine capacity in Europe, 2.5 GW of which was constructed in 2000 compared with only 300 MW in 1993. The average annual growth rate of the installation of wind turbines in Europe from 1993–9 was approximately 40 percent (Zervos, 2000). The distribution of wind-turbine capacity is interesting with, in 2000, Germany accounting for some 45 percent of the European total, and Denmark and Spain each having approximately 18 percent. There is some 2.5 GW of capacity installed in the USA of which 65 percent is in California although with increasing interest in Texas and some states of the Midwest. Many of the California wind farms were originally constructed in the 1980s and are now being re-equipped with larger modern wind turbines.

The reasons development of wind energy in some countries is flourishing while in others it is not fulfilling the potential that might be anticipated from a simple consideration of the wind resource, are complex. Important factors include the financial-support mechanisms for wind-generated electricity, the process by which the local planning authorities give permission for the construction of wind farms, and the perception of the general population particularly with respect to visual impact. In order to overcome the concerns of the rural population over the environmental impact of wind farms there is now increasing interest in the development of sites offshore.

1.3 Modern Wind Turbines

The power output, P, from a wind turbine is given by the well-known expression:

$$P = \frac{1}{2} \rho \, C_P \, A \, U^3 \qquad \cdots \; \cdots \; \cdots \; (1.1)$$

Where, ρ is the density of air ($1.225\ kg/m^3$), C_P is the power coefficient, A is the rotor swept area, and U is the wind speed.

The density of air is rather low, 800 times less than that of water which powers hydro plant, and this leads directly to the large size of a wind turbine. Depending on the design wind speed chosen, a 1.5 MW wind turbine may have a rotor that is more than 60 m in diameter. The power coefficient describes that fraction of the power in the wind that may be converted by the turbine into mechanical work. It has a theoretical maximum value of 0.593 (the Betz limit) and rather lower peak values are achieved in practice. The power coefficient of a rotor varies with the tip speed ratio (the ratio of rotor tip speed to free wind speed) and is only a maximum for a unique tip speed ratio. Incremental improvements in the power coefficient are continually being sought by detailed design changes of the rotor and, by operating at variable speed, it is possible to maintain the maximum power coefficient over a range of wind speeds.

However, these measures will give only a modest increase in the power output. Major increases in the output power can only be achieved by increasing the swept area of the rotor or by locating the wind turbines on sites with higher wind speeds.

Hence over the last 10 years there has been a continuous increase in the rotor diameter of commercially available wind turbines from around 30 m to more than 60 m. A doubling of the rotor diameter leads to a four-times increase in power output. The influence of the wind speed is, of course, more pronounced with a doubling of wind speed leading to an eight-fold increase in power. Thus there have been considerable efforts to ensure that wind farms are developed in areas of the highest wind speeds and the turbines optimally located within wind farms. In certain countries very high towers are being used (more than 60–80 m) to take advantage of the increase of wind speed with height.

In the past a number of studies were undertaken to determine the 'optimum' size of a wind turbine by balancing the complete costs of manufacture, installation and operation of various sizes of wind turbines against the revenue generated (Molly et al., 1993). The results indicated a minimum cost of energy would be obtained with wind turbine diameters in the range of 35–60 m, depending on the assumptions made. However, these estimates would now appear to be rather low and there is no obvious point at which rotor diameters, and hence output power, will be limited particularly for offshore wind turbines.

All modern electricity-generating wind turbines use the lift force derived from the blades to drive the rotor. A high rotational speed of the rotor is desirable in order to reduce the gearbox ratio required and this leads to low solidity rotors (the ratio of blade area/rotor swept area). The low solidity rotor acts as an effective energy concentrator and as a result the energy recovery period of a wind turbine, on a good site, is less than 1 year, i.e., the energy used to manufacture and install the wind turbine is recovered within its first year of operation (Musgrove in Freris, 1990).

1.4 Advantages and Disadvantages of Wind Energy

Wind energy offers many advantages, which explains why it's the fastest-growing energy source in the world. Research efforts are aimed at addressing the challenges to greater use of wind energy.

1.4.1 Advantages

Wind energy is fueled by the wind, so it's a clean fuel source. Wind energy doesn't pollute the air like power plants that rely on combustion of fossil fuels, such as coal or natural gas. Wind turbines don't produce atmospheric emissions that cause acid rain or greenhouse gasses.

Wind energy is a domestic source of energy, produced in the United States. The nation's wind supply is abundant.

Wind energy relies on the renewable power of the wind, which can't be used up. Wind is actually a form of solar energy; winds are caused by the heating of the atmosphere by the sun, the rotation of the earth, and the earth's surface irregularities.

Wind energy is one of the lowest-priced renewable energy technologies available today, costing between 4 and 6 cents per kilowatt-hour, depending upon the wind resource and project financing of the particular project.

Wind turbines can be built on farms or ranches, thus benefiting the economy in rural areas, where most of the best wind sites are found. Farmers and ranchers can continue to work the land because the wind turbines use only a fraction of the land. Wind power plant owners make rent payments to the farmer or rancher for the use of the land.

1.4.2 Disadvantages

Wind power must compete with conventional generation sources on a cost basis. Depending on how energetic a wind site is, the wind farm may or may not be cost competitive. Even though the cost of wind power has decreased dramatically in the past 10 years, the technology requires a higher initial investment than fossil-fueled generators.

The major challenge to using wind as a source of power is that the wind is intermittent and it does not always blow when electricity is needed. Wind energy cannot be stored (unless batteries are used); and not all winds can be harnessed to meet the timing of electricity demands.

Good wind sites are often located in remote locations, far from cities where the electricity is needed.

Wind resource development may compete with other uses for the land and those alternative uses may be more highly valued than electricity generation.

Although wind power plants have relatively little impact on the environment compared to other conventional power plants, there is some concern over the noise produced by the rotor blades, aesthetic (visual) impacts, and sometimes birds have been killed by flying into the rotors. Most of these problems have been resolved or greatly reduced through technological development or by properly sitting wind plants.

2

General Aspects

2.1 Types of wind turbine

Wind turbines can be separated into two types based by the axis in which the turbine rotates. Turbines that rotate around a horizontal axis are more common. Vertical-axis turbines are less frequently used.

- Horizontal axis
- Vertical axis

2.1.1 Horizontal axis

Figure 2.1: Components of a horizontal axis wind turbine (gearbox, rotor shaft and brake assembly) being lifted into position

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 to drive an electrical generator.

Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. 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 (mast wake), because they don't need an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclic (that is repetitive) turbulence may lead to fatigue failures most HAWTs are upwind machines.

2.1.1.1 HAWT Subtypes

Figure 2.2: Doesburger windmill, Ede, The Netherlands.

12th-century windmills

These squat structures, typically (at least) four bladed, usually with wooden shutters or fabric sails, were developed in Europe. These windmills were pointed into the wind manually or via a tail-fan and were typically used to grind grain. In the Netherlands they were also used to pump water from low-lying land, and were instrumental in keeping its polders dry.

In Schiedam, the Netherlands, a traditional style windmill (the *Noletmolen*) was built in 2005 to generate electricity. The mill is one of the tallest Tower mills in the world, being some 42.5 metres (139 ft) tall.

19th-century windmills

The Eclipse windmill factory was set up around 1866 in Beloit, Wisconsin and soon became successful building mills for pumping water on farms and for filling railroad tanks. Other firms like Star, Dempster, and Aero-motor also entered the market. Hundreds of thousands of these mills were produced before rural electrification and small numbers continue to be made. They typically had many blades, operated at tip speed ratios not better than one, and had good starting torque. Some had small direct-current generators used to charge storage batteries, to provide power to lights, or to operate a radio receiver. The American rural electrification connected many farms to centrally-generated power and replaced individual windmills as a primary source of farm power by the 1950s. They were also produced in other countries like South Africa and Australia (where an American design was copied in 1876). Such devices are still used in locations where it is too costly to bring in commercial power.

2.1.1.2 Modern wind turbines

Figure 2.3: The wind turbines on High Knob in the Moosic Mountains of Pennsylvania

Turbines used in wind farms for commercial production of electric power are usually three-bladed and pointed into the wind by computer-controlled motors. These have high tip speeds of up to six times the wind speed, high efficiency, and low torque ripple, which contribute to good reliability. The blades are usually colored light gray to blend in with the clouds and range in length from 20 to 40 meters (65 to 130 ft) or more. The tubular steel towers range from 200 to 300 feet (60 to 90 meters) tall. The blades rotate at 10-22 revolutions per minute. A gear box is commonly used to step up the speed of the generator, although designs may also use direct drive of an annular generator. Some models operate at constant speed, but more energy can be collected by variable-speed turbines which use a solid-state power converter to interface to the transmission system. All turbines are equipped with shut-down features to avoid damage at high wind speeds.

2.1.1.3 HAWT advantages

- Variable blade pitch, which gives the turbine blades the optimum 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.
- 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 moves perpendicularly to the wind, receiving power through the whole rotation. In contrast, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring airfoil surfaces to backtrack against the wind for part of the cycle. Backtracking against the wind leads to inherently lower efficiency.

2.1.1.4 HAWT disadvantages

- The tall towers and blades up to 90 meters long are difficult to transport. Transportation can reach 20% of equipment costs.
- Tall HAWTs are difficult to install, needing very tall and expensive cranes and skilled operators.
- Massive tower construction is required to support the heavy blades, gearbox, and generator.
- Reflections from tall HAWTs may affect side lobes of radar installations creating signal clutter, although filtering can suppress it.

- Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.
- Downwind 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.
- Cyclic stresses and vibration
- Cyclic stresses fatigue the blade, axle and bearing; material failures were a major cause of turbine failure for many years. Because wind velocity often increases at higher altitudes, the backward force and torque on a horizontal-axis wind turbine (HAWT) blade peaks as it turns through the highest point in its circle. The tower hinders the airflow at the lowest point in the circle, which produces a local dip in force and torque. These effects produce a cyclic twist on the main bearings of a HAWT. The combined twist is worst in machines with an even number of blades, where one is straight up when another is straight down. To improve reliability, teetering hubs have been used which allow the main shaft to rock through a few degrees, so that the main bearings do not have to resist the torque peaks.
- The rotating blades of a wind turbine act like a gyroscope. As it pivots along its vertical axis to face the wind, gyroscopic precession tries to twist the turbine disc along its horizontal axis. For each blade on a wind generator's turbine, precessive force is at a minimum when the blade is horizontal and at a maximum when the blade is vertical. This cyclic twisting can quickly fatigue and crack the blade roots, hub and axle of the turbines.

2.1.2 Vertical axis

Vertical-axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable. VAWTs can utilize winds from varying directions.

With a vertical axis, the generator and gearbox can be placed near the ground, so the tower doesn't need to support it, and it is more accessible for maintenance. Drawbacks are that some designs produce pulsating torque. Drag may be created when the blade rotates 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 the 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.

2.1.2.1 VAWT subtypes

Figure 2.4: 30 m Darrieus wind turbine in the Magdalen Islands "Eggbeater" turbines.

2.1.2.1.1 Darrieus wind turbine

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 held up by guy-wires but have an external superstructure connected to the top bearing.

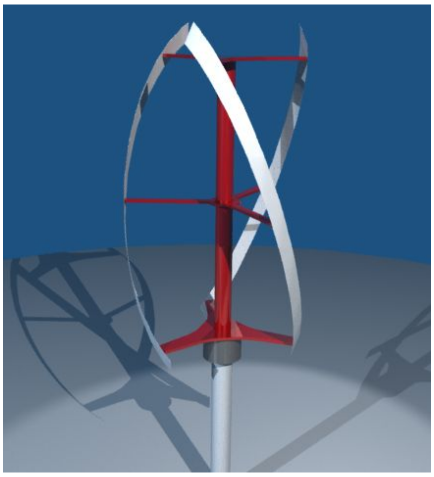


Figure 2.5: A helical twisted VAWT.

2.1.2.1.2 Giromill

A subtype of Darrieus turbine with straight, as opposed to curved, blades. The cycloturbine variety has variable pitch to reduce the torque pulsation and is self-starting. The advantages of variable pitch are: high starting torque; a wide, relatively flat torque curve; a lower blade speed ratio; a higher coefficient of performance; more efficient operation in turbulent winds; and a lower blade speed ratio which lowers blade bending stresses. Straight, V, or curved blades may be used.

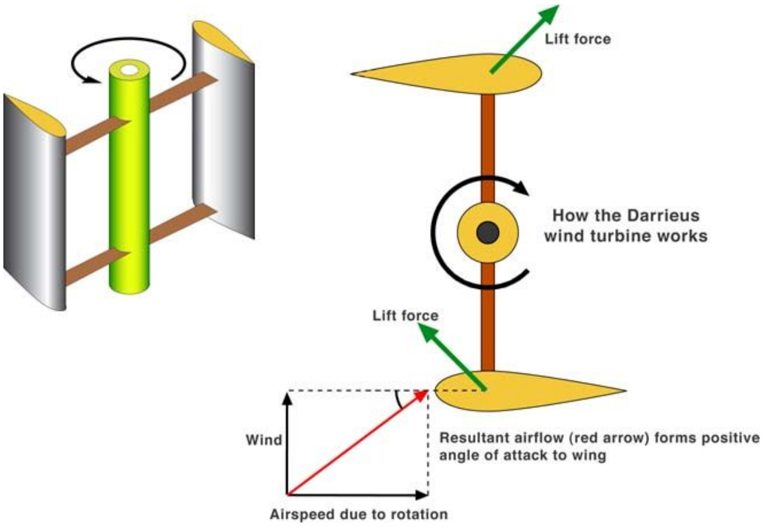


Figure 2.6: Operation of a Giromill

2.1.2.1.3 Savonius wind turbine

These are drag-type devices with two (or more) scoops that are used in anemometers, *Flettner* vents (commonly seen on bus and van roofs), and in some high-reliability low-efficiency power turbines. They are always self-starting if there are at least three scoops. They sometimes have long helical scoops to give a smooth torque.

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. They were invented by the Finnish engineer Sigurd J. Savonius in 1922. Johann Ernst Elias Bessler (born 1680) was the first to attempt to build a horizontal windmill of the Savonius type in the town of Furstenburg in Germany in 1745. He fell to his death whilst construction was under way. It was never completed but the building still exists.

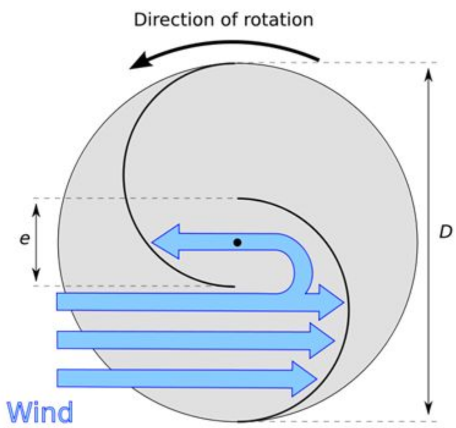


Figure 2.7: Operation of a Savonius turbine

2.1.2.2 VAWT advantages

- A massive tower structure is less frequently used, as VAWTs are more frequently mounted with the lower bearing mounted near the ground, making it easier to maintain the moving parts.
- Designs without yaw mechanisms are possible with fixed pitch rotor designs.
- VAWTs have lower wind startup speeds than HAWTs. Typically, they start creating electricity at 6 mph. (10 km/h).
- VAWTs may be built at locations where taller structures are prohibited.
- VAWTs situated close to the ground can take advantage of locations where mesas, hilltops, ridgelines, and passes funnel the wind and increase wind velocity.
- VAWTs may have a lower noise signature.

2.1.2.3 VAWT disadvantages

- 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.
- A VAWT that uses guy-wires to hold it in place puts stress on the bottom bearing as all the weight of the rotor is on the bearing. Guy wires attached to the top bearing increase downward thrust in wind gusts. Solving this problem requires a superstructure to hold a top bearing in place to eliminate the downward thrusts of gust events in guy wired models.
- While VAWTs' parts are located on the ground, they are also located under the weight of the structure above it, which can make changing out parts nearly impossible without dismantling the structure if not designed properly.
- Having rotors located close to the ground where wind speeds are lower due to wind shear, VAWTs may not produce as much energy at a given site as a HAWT with the same footprint or height.
- Because VAWTs are not commonly deployed due mainly to the serious disadvantages 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.

2.2 Control of wind turbine

There are different controls needed in the wind turbine.

- Power control
  - Stall
  - Pitch control
- Other controls
  - Yawing
  - Electrical braking
  - Mechanical braking

2.2.1 Power control

A wind turbine is designed to produce a maximum of power at wide spectrum of wind speeds. The wind turbines have three modes of operation:

- Below rated wind speed operation
- Around rated wind speed operation
- Above rated wind speed operation

If the rated wind speed is exceeded the power has to be limited. There are various ways to achieve this.

2.2.1.1 Stall

Stalling works by increasing the angle at which the relative wind strikes the blades (angle of attack), and it reduces the induced drag (drag associated with lift). Stalling is simple because it can be made to happen passively (it increases automatically when the winds speed up), but it increases the cross-section of the blade face-on to the wind, and thus the ordinary drag. A fully stalled turbine blade, when stopped, has the flat side of the blade facing directly into the wind.

A fixed-speed HAWT inherently increases its angle of attack at higher wind speed as the blades speed up. A natural strategy, then, is to allow the blade to stall when the wind speed increases. This technique was successfully used on many early HAWTs. However, on some of these blade sets, it was observed that the degree of blade pitch tended to increase audible noise levels.

2.2.1.2 Pitch control

Furling works by decreasing the angle of attack, which reduces the induced drag from the lift of the rotor, as well as the cross-section. One major problem in designing wind turbines is getting the blades to stall or furl quickly enough should a gust of wind cause sudden acceleration. A fully furled turbine blade, when stopped, has the edge of the blade facing into the wind.

Standard modern turbines all pitch the blades in high winds. Since pitching requires acting against the torque on the blade, it requires some form of pitch angle control. Many turbines use hydraulic systems. These systems are usually spring loaded, so that if hydraulic power fails, the blades automatically furl. Other turbines use an electric servomotor for every rotor blade. They have a small battery-reserve in case of an electric-grid breakdown. Small wind turbines (under 50 kW) with variable-pitching generally use systems operated by centrifugal force, either by flyweights or geometric design, and employ no electric or hydraulic controls.

2.2.2 Other controls

2.2.2.1 Yawing

Modern large wind turbines are typically actively controlled to face the wind direction measured by a wind vane situated on the back of the nacelle. By minimizing the yaw angle (the misalignment between wind and turbine pointing direction), the power output is maximized and non-symmetrical loads minimized. However, since the wind direction varies quickly the turbine will not strictly follow the direction and will have a small yaw angle on average. The power output losses can simplified be approximated to fall with $\cos^3$ (yaw angle).

2.2.2.2 Electrical braking

Figure 2.8: Electrical braking resistor for wind turbine.

Braking of a small wind turbine can also be done by dumping energy from the generator into a resistor bank, converting the kinetic energy of the turbine rotation into heat. This method is useful if the kinetic load on the generator is suddenly reduced or is too small to keep the turbine speed within its allowed limit.

Cyclically braking causes the blades to slow down, which increases the stalling effect, reducing the efficiency of the blades. This way, the turbine's rotation can be kept at a safe speed in faster winds while maintaining (nominal) power output. This method is usually not applied on large grid-connected wind turbines.

2.2.2.3 Mechanical braking

A mechanical drum brake or disk brake is used to hold the turbine at rest for maintenance. Such brakes are usually applied only after blade furling and electromagnetic braking have reduced the turbine speed, as the mechanical brakes would wear quickly if used to stop the turbine from full speed. There can also be a stick brake.

2.3 The controller

In one way or another controller is involved in almost all decision-making processes in the safety systems in a wind turbine. At the same time it must oversee the normal operation of the wind turbine and carry out measurements for statistical use etc.

The controller is based on the use of a micro computer, specially designed for industrial use and therefore not directly comparable with a normal PC. It has a capacity roughly equivalent to that of an

80286 PC system processor. The control program itself is not stored in a hard disk, but is stored in a microchip called an EPROM. The processor that does the actual calculations is likewise a microchip.

Most wind turbine owners are familiar with the normal keyboard and display unit used in wind turbine control. The computer is placed in the control cabinet together with a lot of other types of electro-technical equipment, contactors, switches, fuses, etc.

The many and varied demands of the controller result in a complicated construction with a large number of different components. Naturally, the more complicated a construction and the larger the number of individual components that are used in making a unit, the greater the possibilities for errors. This problem must be solved, when developing a control system that should be as fail-safe as possible.

To increase security measures against the occurrence of internal errors, one can attempt to construct a system with as few components as possible. It is also possible to build-in an internal automatic 'self-supervision', allowing the controller to check and control its own systems. Finally, an alternative parallel back-up system can be installed, having more or less the same functions, but assembled with different types of components. On the 600 kW Mk. IV wind turbine, all three principles are used in the control and safety systems. These will be further discussed one at a time in the following.

- A series of sensors measure the conditions in the wind turbine. These sensors are limited to those that are strictly necessary. This is the first example of the targeted approach towards fail-safe systems. One would otherwise perhaps think, as we now have access to computers and other electronic devices with almost unlimited memory capacity, that it would merely be a matter of measuring and registering as much as possible. However this is not the case, as every single recorded measurement introduces a possibility for error, no matter how high a quality of the installed sensors, cables and computer. The choice of the necessary sensors is therefore to a high degree a study in the art of limitation.

The controller measures the following parameters as analogue signals (where measurements give readings of varying values):

- Voltage on all three phases
- Current on all three phases
- Frequency on one phase
- Temperature inside the nacelle
- Generator temperature
- Gear oil temperature
- Gear bearing temperature
- Wind speed
- The direction of yawing
- Low-speed shaft rotational speed
- High-speed shaft rotational speed

Other parameters that are obviously interesting are not measured, electrical power for example. The reasons being that these parameters can be calculated from those are in fact measured. Power can thus be calculated from the measured voltage and current.

The controller also measures the following parameters as digital signals (where the measurements do not give readings of varying values, but a mere an on/off signal):

- Wind direction
- Over-heating of the generator
- Hydraulic pressure level
- Correct valve function
- Vibration level
- Twisting of the power cable
- Emergency brake circuit
- Overheating of small electric motors for the yawing, hydraulic pumps, etc.
- Brake-caliper adjustment
- Centrifugal-release activation

Even though it is necessary to limit the number of measurements, certain of these are duplicated, for example at the gearbox, the generator and the rotational speed. In these cases we consider that the increased safety provided, is more important than the risk of possible sensory failure.

Internal supervision is applied on several levels. First of all the computer is equipped with certain control functions, known as ‘watchdogs’. These supervise that the computer does not make obvious calculation errors. In addition the wind turbine software itself has extra control functions. For example, the cases of wind speed parameters. A wind turbine is designed to operate at wind speeds up to 25 m/s, and the signal from the anemometer (wind speed indicator) is used in taking the decision to stop the wind turbine, as soon as the wind speed exceeds 25 m/s.

Figure2.9: Cup anemometer for wind speed indication (left) * Lightning conductor (middle) * Wind direction indicator (right)

As a control function of the anemometer the controller supervises wind speed in relation to power. The controller will stop the wind turbine and indicate a possible wind measurement error, if too much power is produced during a period of low wind, or too little power during a period of high wind.

A wind measurement error could be caused by a fault in the electrical wiring, or a defect bearing in the anemometer. A constant functional check of the relationship between wind speed and power production ensures that it is almost impossible for the wind turbine to continue operation with a wind measurement error, and the possibility of a wind turbine being subject to stronger winds than its designed wind speed rating, is therefore more or less eliminated.

The third safety principle for the controller lies in duplication of systems. A good example is the mechanical centrifugal release units. These supervise the blade rotational speed and activate the braking systems, even if the speed measurement system of the controller should fail.

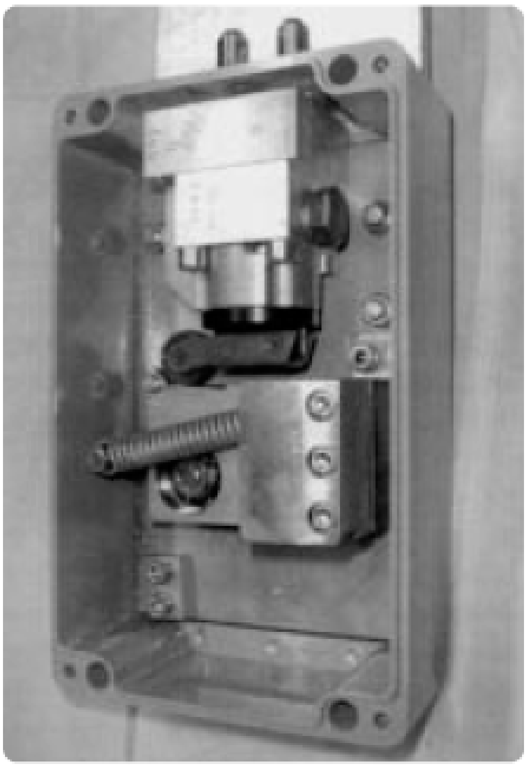


Figure 2.10: Interior view of the CU

A 600 kW Mk IV wind turbine has two centrifugal release units. One of these is hydraulic and placed on the wind turbine hub. It is normally called a CU (Centrifugal release Unit). Should the wind turbine operate at too high a rotational speed, a weight will be thrown out and thereby open a hydraulic valve.

Once the valve is open, hydraulic oil will spill out from the hydraulic cylinders that hold the blade tips in place, thereby activating the blade tip air brakes. No matter what actions the controller or the hydraulic system thereafter attempts to carry out, pressure cannot be maintained in the cylinders and the air brakes will continue to remain activated, until a serviceman resets the centrifugal release manually.

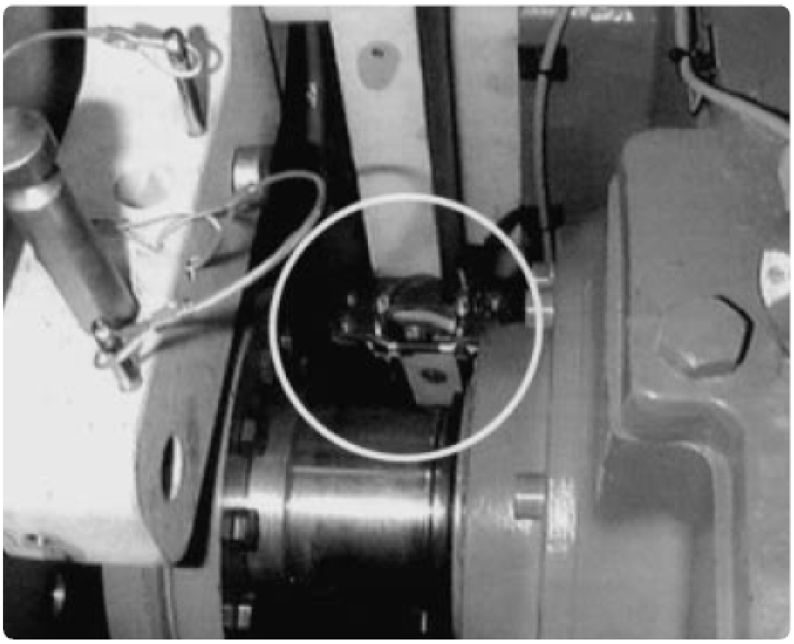


Figure 2.11: HCU placed on the high speed shaft of the gearbox

The advantages of the hydraulic centrifugal release units is that it is completely independent the controller and the hydraulic system. This ensures that a possible fatal software design error, not discovered during design review, will not result in a possible run-away of the wind turbine.

The second centrifugal release unit is an electro-mechanical unit, fixed to the high speed shaft of the gearbox. This is normally called an HCU, where H is short for 'high-speed'. Should the wind turbine over-speed, two small arms are thrown out mechanically cutting off the electrical current to the magnetic valves of the air brakes and the mechanical braking system.

This is a so-called fail-safe system, where the electrical circuit must remain switched on in order to maintain the valves for the air brakes and for the mechanical brake in a closed position. Should the electrical circuit be broken because of a disconnection from the grid or as a result of a shut down from the controller itself, the valves will open and activate the brakes causing the wind turbine to slow down and stop.

The HCU is able to mechanically cut the braking circuit, and thereby activate both braking systems. The hub-mounted CU only cuts the blade hydraulic system. The HCU therefore is superior; however its successful operation is based in turn upon satisfactory operation of the normal valve systems, while the CU has its own extra valve system. Both systems thus have their own advantages and disadvantages considered from the point of view of safety.

Both centrifugal release units are adjusted to be activated at very near the normal operational rotational speed, therefore, on rare occasions, release can occur prematurely. This is not normally the case in Denmark, but following from unexpected power cuts at certain foreign projects, causing the turbines shortly to operate in stand-alone mode, we have experienced release activation. Otherwise centrifugal release systems are only intended to be activated during maintenance testing.

2.4 Working principle of wind turbine

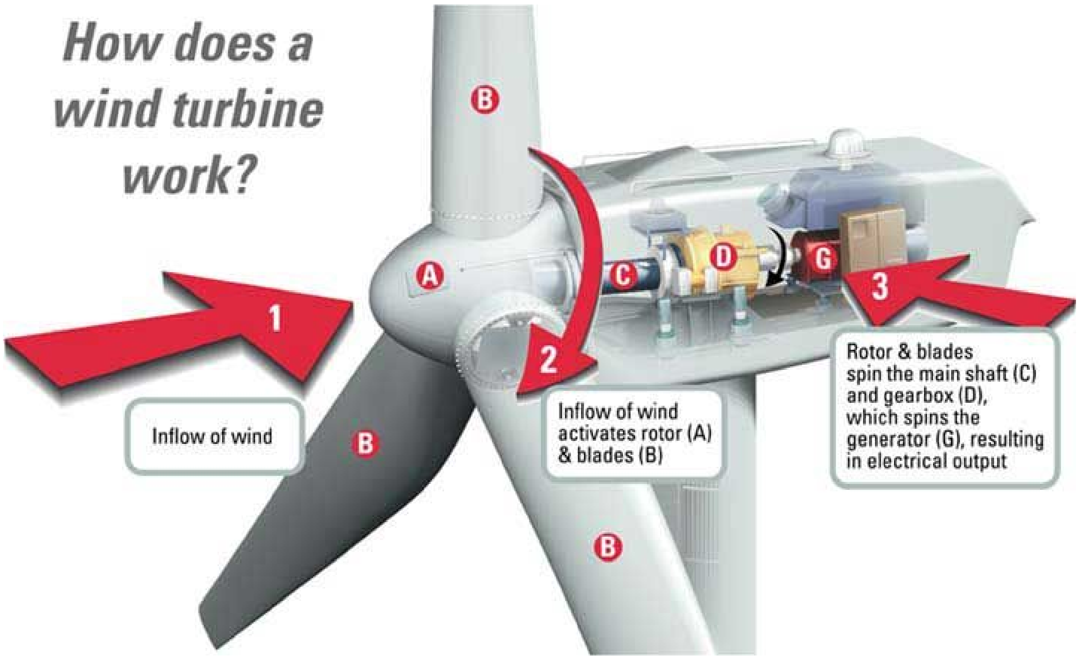


Figure 2.12: Working method of wind turbine

Wind is merely air in motion. Wind turbines convert kinetic energy from the wind that passes over the rotors into electricity.

Wind turbines consist of four main components—the rotor, transmission system, generator, and yaw and control systems—each of which is designed to work together to reliably convert the motion of the wind into electricity. These components are fixed onto or inside the nacelle, which is mounted on the tower. The nacelle rotates (or yaws) according to the wind direction.

The Cape Wind project will utilize tubular steel towers that result in an overall hub height of 246 feet above mean sea level and which are secured onto a single (monopole) foundation. Each tower allows internal access via ladders and platforms. The tower and foundation system are designed to withstand high winds, earthquakes, high waves, ice and other damaging elements that may be encountered.

Once the electricity is produced in each turbine's generator, a transformer located in the nacelle increases the voltage to 34.5kV. Then it is tied into a grid, which has between 10 and 15 turbines connected on it. The 34.5kV grid cable is buried six feet below the bottom surface and is connected to the electronic service platform (ESP). On the ESP, the voltage is increased to 115kV and transmitted to shore in two cables, which also will be buried six feet below the bottom surface. The ESP is fitted with circuit breakers and electric relays to protect the electrical system, as well as the control systems.

2.5 How Wind Turbines are rated

Wind turbine rating is a tricky affair. While solar-electric module or micro-hydro-electric turbine production can be predicted fairly realistically based on rated output, this number is very misleading with wind turbines. Because rated output is pegged to a particular wind speed, and different manufacturers use different wind speeds to determine rated output. Also, the power available in the wind varies with the cube of its speed, so small increases in wind speed result in large increases in power available to the rotor. A 10 percent increase in wind speed yields a 33 percent increase in power available in the wind. Conversely, this means that a turbine rated at 1,000 watts at 28 mph might produce only 125 watts or less at half that wind speed, 14 mph.

A wind turbine buyer can do just ignore the peak output and the power curve. Look for the monthly or annual energy numbers for the turbine, estimated for the average wind speed we expect or measure at our site. These will be given in KWH per month (or year) in the manufacturer´s specifications for each turbine. Energy is what is after, not peak power! If, for example, we are looking for a turbine that can produce 300 KWH per month, and we know that we have a 10 mph average wind speed at the proposed turbine height, we can shop for a turbine that is predicted to generate that much energy in that average wind speed.

If we can´t get energy production estimates from the manufacturer or a turbine owner, look for a different manufacturer. This is basic information that any manufacturer should supply. However, knowing a turbine´s swept area may also help we calculate the annual energy output for the wind turbine. All other things being equal, ″there´s no replacement for displacement.″ Hugh Piggott gives a rough formula for calculating output based on average wind speed and swept area in his HP102 article. Jim Green at the National Renewable Energy Lab (NREL) developed a similar formula:

$$\begin{aligned}&\text{Annual energy output (AEO) in KWH} = \\ &\quad 0.01328 \times (\text{rottor diameter in feet})^2 \times \{\text{Average wind speed in (mph)}\}^3 \qquad \cdots\cdots\cdots (2.1)\end{aligned}$$

A turbine´s revolution per minute (rpm) at its rated wind speed can give us some idea of the relative aerodynamic sound of the machine, and also speaks to longevity. Slower-turning wind turbines tend to be quieter and last longer. High rpm machines wear out components, such as bearings, much faster. In addition, the faster blades move through the air, the greater the possibility that they will waste some of that energy as sound from the blades.

2.6 How to Choose a Wind Turbine

Trying to keep an inexpensive wind generator running can be an uphill battle that we´ll soon tire of. But expect to pay more for a better machine—it´s a tough job to design and manufacture a long-lasting, small-scale wind generator.

The bottom line: Buy a turbine that has a very good track record and a good warranty—five years is preferable but not always available in the small wind industry. A warranty is one indication of the manufacturer´s confidence in their product, and their intention to stand behind it.

Real-world reports from users carry even more weight than a warranty, so search for people who own the model of turbine we´re considering buying, and get the straight scoop from them about performance, durability, reliability, and maintenance issues.

Note that a number of the wind turbines listed here are relatively new introductions with not very much customer run-time in North America. These turbines include the ARE, Eoltec, Kestrel, and Skystream. We recommend that you contact either our local wind turbine installer, or the manufacturers or importers and find out how many of these machines are actually operating in North America. Then contact the owners, and inquire about their experience and satisfaction with both the machine and the manufacturer or importer.

Some manufacturers make only battery-charging machines, and may offer a variety of turbine voltages. Others produce machines intended to connect to grid-synchronous inverters without batteries. One machine even includes an inverter integrated with the turbine itself. Make sure we´re buying a machine that is appropriate for our intended use.

When we look at prices, keep in mind that just buying a wind turbine will not get us any wind-generated electricity. We´ll also need most or all of the components mentioned elsewhere. Also budget for equipment rental, like a backhoe and crane, concrete and rebar, electrical components, shipping, and sales tax. Unless we do all of the work our self, also factor in installation labor expenses. These costs can add up significantly, so make sure that we research and understand all of the associated expenses before committing to a purchase. Many people are quite surprised to learn that the wind turbine cost can range from only 10 percent to as much as 40 percent of the entire wind system´s expenses.

Small-scale wind energy is not for the half-hearted, uninvolved, or uncommitted, and probably not for folks who never change the oil in their vehicles (or are willing to spend the bucks to hire someone to do the tower work). The North American landscape is littered with failed installations: Designs not fully thought-out or tested, machines bought because they were cheap, and installations that required more time and money for repairs than they ever yielded in electricity generated. Many of the failures were the result of wishful thinking and too little research. That said, there are tens of thousands of happy wind-electric system owners. These owners did their homework—purchasing, designing, and installing rugged and well-thought-out systems on adequately sized towers. In addition, they are either committed to maintaining the systems, or to hiring someone to do this regular work.

While many first-time wind turbine buyers may be looking for a bargain, second-time wind turbine buyers are seeking the most rugged machine they can afford. We can avoid a painful "learning experience" by focusing on durability, production, warranty, and track record, and not on price alone, or on peak output. We don´t want to depend on the low bidder for something as important to we as our long-term energy investment.

2.7 Wind turbine efficiency

According to David Rosser- director of CBI Wales the wind only blows strongly enough 10% of the time for a wind energy project to work. According to James May from Top Gear on his latest TV show, wind turbines only work 30% of the time. Why do people who are anti-wind energy keep using this against wind when they are so easily proven wrong? People with responsibility for disseminating information should check their facts.

To try and help stop the confusion, here are the facts:

i. A modern wind turbine has a maximum capacity of around 2000 kilowatts (kW) or 2 Megawatts (MW)
ii. There are 8760 hours in a year (365 days x 24 hours)
iii. A 2 MW wind turbine will generate around 30% of its maximum theoretical capacity resulting in 5256 Megawatt hours (MWH) generated per turbine per year
iv. Taking all of the above into consideration a wind turbine will generate enough green electricity for the average annual needs of around 1100 homes, using an average demand of 4700 kWh per house based on electricity consumption figures from Digest of UK Energy Statistics

Wind turbines usually operate 75-90% of the time - but not at full capacity.

2.8 Wind-Electric System Types

2.8.1 Off-Grid Wind-Electric Systems

Off-grid wind-electric systems are battery based. People generally choose these systems because their home or other energy use is not connected to the grid, and connection would be expensive. Others prefer the independence of off-grid systems, or live where utilities and governments make it difficult to tie a renewable energy system to the grid.

Off-grid systems are limited in capacity by the size of the generating sources (wind turbine, solar-electric array, fuel-fired generator, etc.), the resources available, and the battery bank size. Off-grid homeowners have to learn to live within the limitations of their system capacity.

The following illustration includes the primary components of any off-grid wind-electric system with battery backup. See our Wind-Electric System Components section for an introduction to the function(s) of each component.

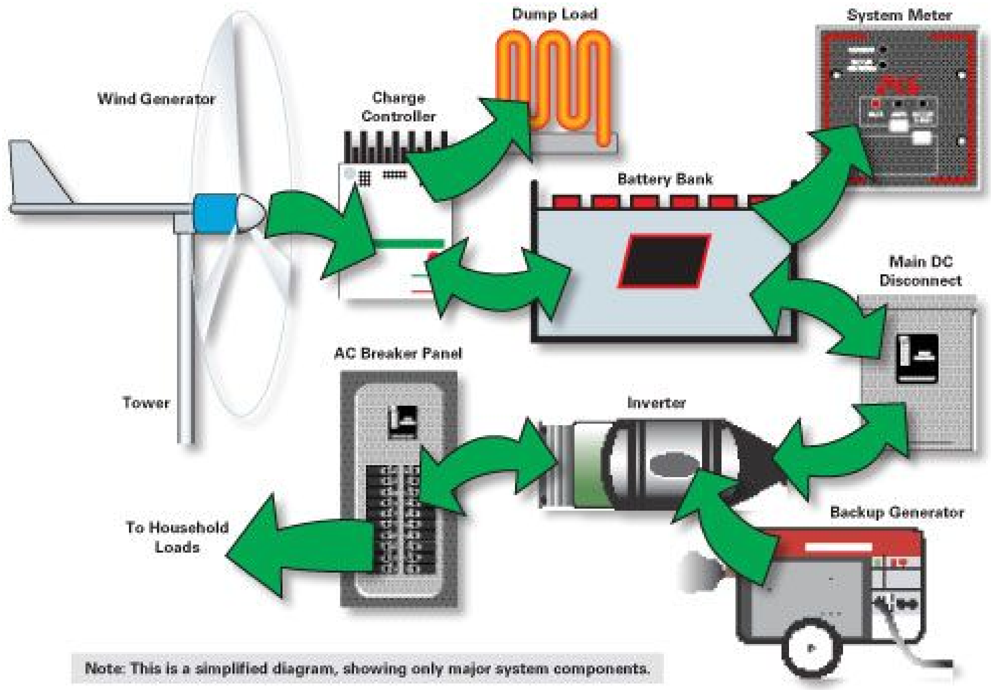


Figure 2.13: Off-Grid Wind-Electric Systems

2.8.2 Grid-Tied Wind-Electric System with Battery Backup

Connecting a wind-electric system to the utility grid with battery backup gives us the best of both worlds. We have the unlimited capacity of the grid at our disposal, and we can send our surplus wind energy to the grid. When the grid is down, we can still use our system, within the limitations of the battery bank and turbine. Wind-electric systems can be a much better match for utility backup than solar-electric systems, since many grid outages are caused by high winds. The drawback is that this is the most expensive type of wind-electric system we can install.

The following illustration includes the primary components of any grid-tied wind-electric system with battery backup. See our Wind-Electric System Components section for an introduction to the function(s) of each component.

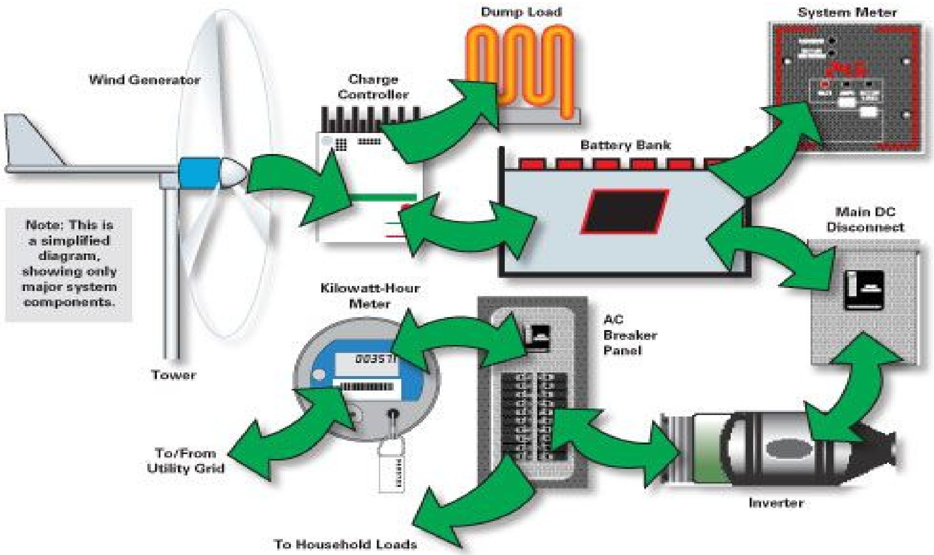


Figure 2.14: Grid-Tied Wind-Electric System with Battery Backup

2.8.3 Battery-less Grid-Tied Wind-Electric System

Connecting to the grid without batteries is the most cost-effective and environmentally friendly way to go. We eliminate batteries, which are costly, require maintenance, and carry a significant efficiency penalty. The only drawback of battery-less systems is that when the grid is down, our system shuts down. But in most grid-serviced areas, utility outages are only a few hours a year—a small inconvenience to endure for the efficiency, environmental friendliness, and thriftiness of these systems.

Battery-less grid-tie systems may see increased performance (sometimes dramatically) from the wind turbine compared to battery-based systems. This is because the inverter´s electronics can match the wind´s load more exactly, running the turbine at optimum speed, and extracting the maximum energy.

The following illustration includes the primary components of any battery-less grid-tied wind-electric system. See our Wind-Electric System Components section for an introduction to the function(s) of each component.

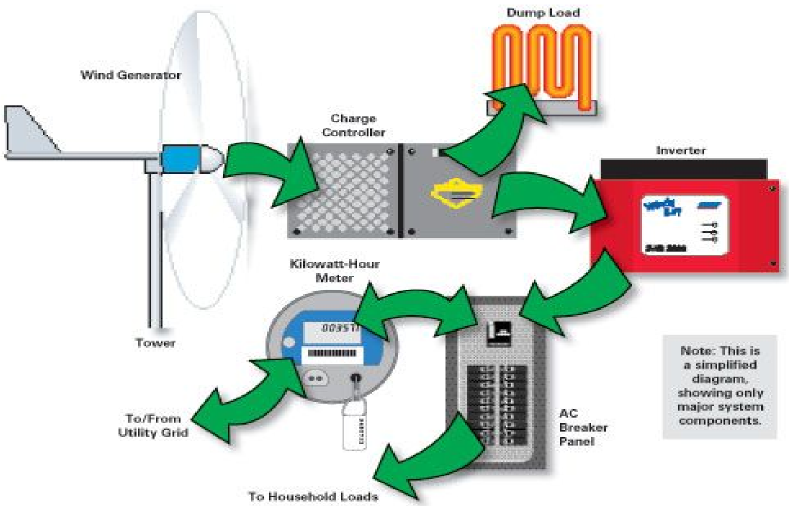


Figure 2.15: Battery-less Grid-Tied Wind-Electric System

2.8.4 Direct-Drive Battery-less Wind-Electric System

These are the least common wind-electric systems, typically used for water pumping. A turbine is matched to a pump, often through an electronic controller. When the wind blows, water is pumped to an elevated tank, a stock-watering tank, or directly to the land to irrigate. These systems can be simple and cost effective in the right situation. Direct-drive systems are also used for heating, which can be a good match, since it´s normally colder when it´s windy. But heating is a big load, so large turbines are needed. The following illustration includes the primary components of any battery-less grid-tied wind electric system.

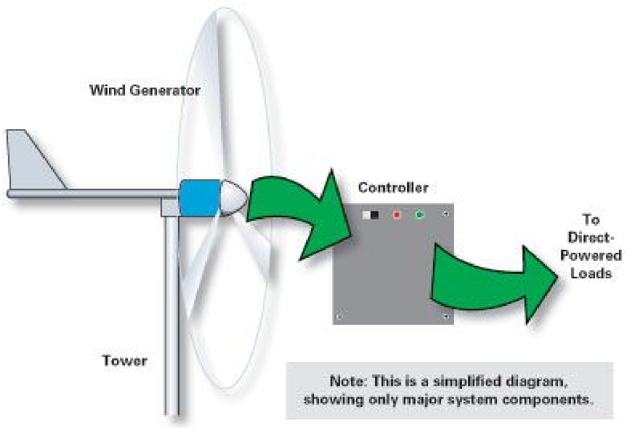


Figure 2.16: Direct-Drive Battery-less Wind-Electric System

3

Wind Turbine Design

3.1 Introduction of wind turbine design

Wind turbines are designed to exploit wind energy. Fundamental aerodynamic theory shows that not all the energy of the wind at a given point can be extracted (see Betz limit), and a practical design can only obtain around 80% of the theoretical maximum. A wind turbine installation consists of sub-systems to catch the wind's energy, point the turbine into the wind, convert mechanical rotation into electrical power, and systems to start, stop, and control the turbine. This article covers the design of horizontal-axis wind turbines (HAWT) since the majority of commercial turbine uses this design.

3.2 Design specification

The design specification for a wind-turbine will contain a power curve and guaranteed availability. With the data from the wind resource assessment it is possible to calculate commercial viability. The typical operating temperature range is (-20 to 40°C) (−4 to 104 °F). In areas with extreme climate (like Inner Mongolia or Rajasthan) specific cold and hot weather versions are required.

3.2.1 Low temperature

Utility-scale wind turbine generators have minimum temperature operating limits which apply in areas that experience temperatures below –20 °C. Wind turbines must be protected from ice accumulation, which can make anemometer readings inaccurate and which can cause high structure loads and damage. Some turbine manufacturers offer low-temperature packages at a few percent extra cost, which include internal heaters, different lubricants, and different alloys for structural elements. If the low-temperature interval is combined with a low-wind condition, the wind turbine will require an external supply of power, equivalent to a few percent of its rated power, for internal heating. For example, the St. Leon, Manitoba project has a total rating of 99 MW and is estimated to need up to 3 MW (around 3% of capacity) of station service power a few days a year for temperatures down to –30 °C. This factor affects the economics of wind turbine operation in cold climates.

3.3 Wind turbine aerodynamics

The aerodynamics of a horizontal-axis wind turbine (HAWT) is not straight forward. The air flow at the blades is not the same as the airflow far away from the turbine. The very nature of the way in which energy is extracted from the air also causes air to be deflected by the turbine. In addition the aerodynamics of a wind turbine at the rotor surface exhibit phenomena that are rarely seen in other aerodynamic fields.

3.3.1 Axial momentum and the Betz limit

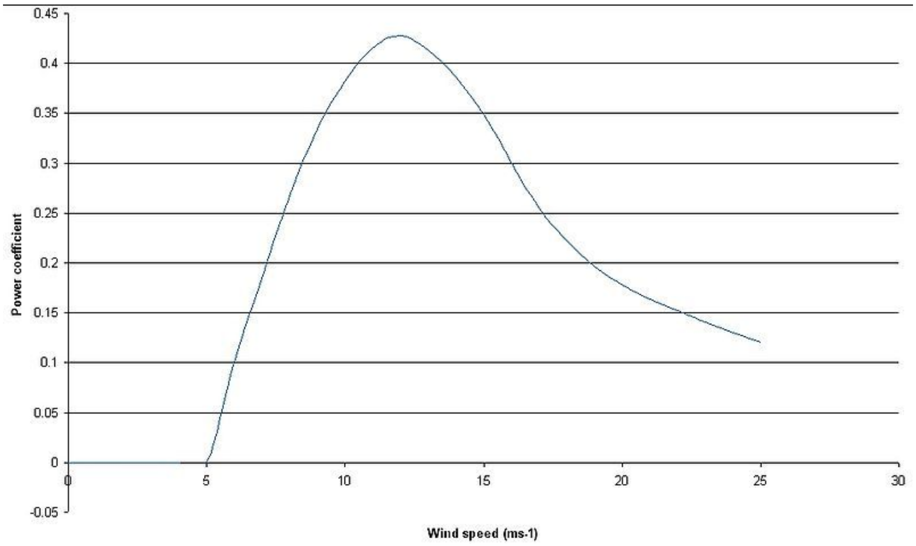


Figure 3.1: Wind turbine power coefficient

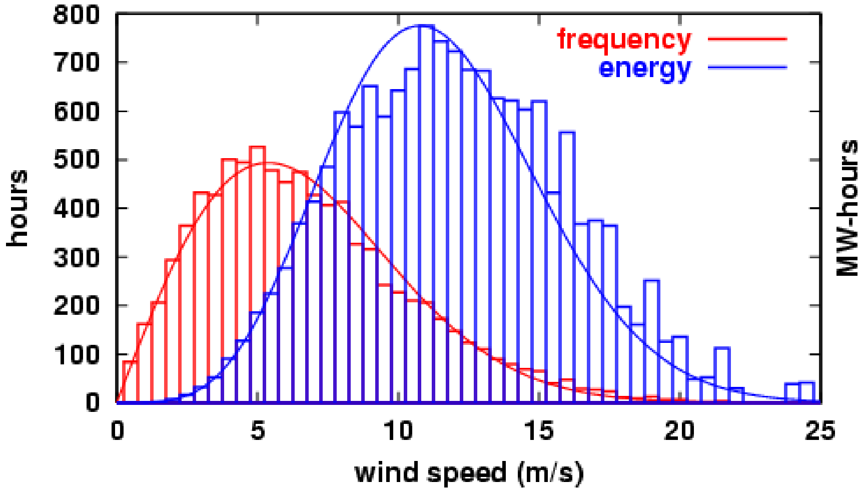


Figure 3.2: Distribution of wind speed (red) and energy generated (blue).

The histogram shows measured data, while the curve is the Raleigh model distribution for the same average wind speed.

Energy in fluid is contained in four different forms: gravitational potential energy, thermodynamic pressure, kinetic energy from the velocity and finally thermal energy. Gravitational and thermal energy have a negligible effect on the energy extraction process. From a macroscopic point of view, the air flow about the wind turbine is at atmospheric pressure. If pressure is constant then only kinetic energy is extracted. However up close near the rotor itself the air velocity is constant as it passes through the rotor plane. This is because of conservation of mass. The air that passes through the rotor cannot slow down because it needs to stay out of the way of the air behind it. So at the rotor the energy is extracted by a pressure drop. The air directly behind the wind turbine is at sub-atmospheric pressure; the air in front is under greater than atmospheric pressure. It is this high pressure in front of the wind turbine that deflects some of the upstream air around the turbine.

Albert Betz was together with Lancaster the first to study this phenomenon. He notably determined the maximum limit to wind turbine performance. The limit is now referred to as the Betz limit. This is derived by looking at the axial momentum of the air passing through the wind turbine. As stated above some of the air is deflected away from the turbine. This causes the air passing through the rotor plane to have a smaller velocity than the free stream velocity. The ratio of this reduction to that of the air velocity far away from the wind turbine is called the axial induction factor. It is defined as below.

$$a \equiv \frac{U_1 - U_2}{U_1} \qquad \cdots \cdots \cdots (3.1)$$

Where, a is the axial induction factor. U_1 is the wind speed far away upstream from the rotor. U_2 is the wind speed at the rotor.

The first step to deriving the Betz limit is applying conservation of axial momentum. As stated above the wind loses speed after the wind turbine compared to the speed far away from the turbine. This would violate the conservation of momentum if the wind turbine was not applying a thrust force on the flow. This thrust force manifests itself through the pressure drop across the rotor. The front operates at high pressure while the back operates at low pressure. The pressure difference from the front to back causes the thrust force. The momentum lost in the turbine is balanced by the thrust force. Another equation is needed to relate the pressure difference to the velocity of the flow near the turbine. Here the Bernoulli equation is used between the field flow and the flow near the wind turbine. There is one limitation to the Bernoulli equation: the equation cannot be applied to fluid passing through the wind turbine. Instead conservation of mass is used to relate the incoming air to the outlet air. Betz used these equations and managed to solve the velocities of the flow in the far wake and near the wind turbine in terms of the far field flow and the axial induction factor. The velocities are given below.

$$U_2 = U_1(1 - a) \qquad \cdots \cdots \cdots (3.2)$$

$$U_4 = U_1(1 - 2a) \qquad \cdots \cdots \cdots (3.3)$$

U_4 is introduced here as the wind velocity in the far wake. This is important because the power extracted from the turbine is defined by the following equation. However the Betz limit is given in terms of the coefficient of power. The coefficient of power is similar to efficiency but not the same. The formula for the coefficient of power is given beneath the formula for power.

$$P = 0.5\rho A U_2 (U_1{}^2 - U_4{}^2) \qquad \cdots \cdots \cdots (3.4)$$

$$C_p \equiv \frac{P}{0.5\rho A U_1{}^3} \qquad \cdots \cdots \cdots (3.5)$$

Betz was able to develop an expression for Cp in terms of the induction factors. This is done by the velocity relations being substituted into power and power is substituted into the coefficient of power definition. The relationship Betz developed is given below.

$$C_p = 4a(1 - a)^2 \qquad \cdots \cdots \cdots (3.6)$$

The Betz limit is defined by the maximum value that can be given by the above formula. This is found by taking the derivative with respect to the axial induction factor, setting it to zero and solving for the axial induction factor. Betz was able to show that the optimum axial induction factor is one third. The optimum axial induction factor was then used to find the maximum coefficient of power. This maximum coefficient is the Betz limit. Betz was able to show that the maximum coefficient of power of a wind turbine is $16/27$. Airflow operating at higher thrust will cause the axial induction factor to rise above the optimum value. Higher thrust cause more air to be deflected away from the turbine. When the axial induction factor falls below the optimum value the wind turbine is not extracting all the energy it can. This reduces pressure around the turbine and allows more air to pass through the turbine, but not enough to account for lack of energy being extracted.

The derivation of the Betz limit shows a simple analysis of wind turbine aerodynamics. In reality there is a lot more. A more rigorous analysis would include wake rotation, the effect of variable geometry. The effect of air foils on the flow is a major component of wind turbine aerodynamics. Within airfoils alone, the wind turbine aerodynamicist has to consider the effect of surface roughness, dynamic stall tip losses, solidity, among other problems.

3.3.2 Angular momentum and wake rotation

The wind turbine described by Betz does not actually exist. It is merely an idealized wind turbine described as an actuator disk. Its a disk in space where fluid energy is simply extracted from the air. In the Betz turbine the energy extraction manifests itself through thrust. The equivalent turbine described by Betz would be a horizontal propeller type operating with infinite blades at infinite tip speed ratios and no losses. The tip speed ratio is ratio of the speed of the tip relative to the free stream flow. This turbine is not too far from actual wind turbines. Actual turbines are rotating blades. They typically operate at high tip speed ratios. At high tip speed ratios three blades are sufficient to interact with all the air passing through the rotor plane. Actual turbines still produce considerable thrust forces.

One key difference between actual turbines and the actuator disk, is that the energy is extracted through torque. The wind imparts a torque on the wind turbine, thrust is a necessary by-product of torque.

Newtonian physics dictates that for every action there is an equal and opposite reaction. If the wind imparts a torque on the blades then the blades must be imparting a torque on the wind. This torque would then cause the flow to rotate. Thus the flow in the wake has two components, axial and tangential. This tangential flow is referred to as wake rotation.

Torque is necessary for energy extraction. However wake rotation is considered a loss. Accelerating the flow in the tangential direction increases the absolute velocity. This in turn increases the amount of kinetic energy in the near wake. This rotational energy is not dissipated in any form that would allow for a greater pressure drop (Energy extraction). Thus any rotational energy in the wake is energy that is lost and unavailable.

This loss is minimized by allowing the rotor to rotate very quickly. To the observer it may seem like the rotor is not moving fast; however, it is common for the tips to be moving through the air at 6 times the speed of the free stream. Newtonian mechanics defines power as torque multiplied by the rotational speed. The same amount of power can be extracted by allowing the rotor to rotate faster and produce less torque. Less torque means that there is less wake rotation. Less wake rotation means there is more energy available to extract.

3.3.3 Blade Element and Momentum Theory

The simplest model for Horizontal Axis Wind Turbine Aerodynamics is Blade Element Momentum (BEM) Theory. The theory is based on the assumption that the flow at a given annulus does not affect the flow at adjacent annuli. This allows the rotor blade to be analyzed in sections, where the resulting forces are summed over all sections to get the overall forces of the rotor. The theory uses both axial and angular momentum balances to determine the flow and the resulting forces at the blade.

The momentum equations for the far field flow dictate that the thrust and torque will induce a secondary flow in the approaching wind. This in turn affects the flow geometry at the blade. The blade itself is the source of these thrust and torque forces. The force response of the blades is governed by the geometry of the flow, or better known as the angle of attack. Refer to the Airfoil article for more information on how airfoils create lift and drag forces at various angles of attack. This interplay between the far field momentum balances and the local blade forces requires one to solve the momentum equations and the airfoil equations simultaneously. Typically computers and numerical methods are employed to solve these models.

There is a lot of variation between different version of BEM theory. First, one can consider the effect of wake rotation or not. Second, one can go further and consider the pressure drop induced in wake rotation. Third, the tangential induction factors can be solved with a momentum equation, an energy balance or orthognal geometric constraint; the latter a result of Biot-Savart law in vortex methods. These all lead to different set of equations that need to be solved. The simplest and most widely used equations are those that consider wake rotation with the momentum equation but ignore the pressure drop from wake rotation. Those equations are given below. a is the axial component of the induced flow, a' is the tangential component of the induced flow. γ is the solidity of the rotor, φ is the local inflow angle. C_n and C_t are the coefficient of normal force and the coefficient of tangential force respectively. Both these coefficients are defined with the resulting lift and drag coefficients of the airfoil.

$$a = \frac{1}{\frac{4\,sin^2\varphi}{C_n\,\gamma} + 1} \quad \cdots\cdots\cdots (3.7)$$

$$a' = \frac{1}{\frac{4\,sin\varphi\;cos\varphi}{C_t\,\gamma} - 1} \quad \cdots\cdots\cdots (3.8)$$

3.3.3.1 Corrections to Blade Element Momentum Theory

Blade Element Momentum (BEM) theory alone fails to accurately represent the true physics of real wind turbines. Two major shortcomings are the effect of discrete number of blades and far field effects when the turbine is heavily loaded. Secondary short-comings come from dealing with transient effects like dynamic stall, rotational effects like coriolis and centrifugal pumping, finally geometric effects that arise from coned and yawed rotors. The current state of the art in BEM uses corrections to deal with the major shortcoming. These corrections are discussed below. There is as yet no accepted treatment for the secondary shortcomings. These areas remain a highly active area of research in wind turbine aerodynamics.

The effect of the discrete number of blades is dealt with by applying the Prandtl tip loss factor. The most common form of this factor is given below where N is the number of blades, R is the outer radius and r is the local radius. The definition of F is based on actuator disk models and not directly applicable to BEM. However the most common application multiplies induced velocity term by F in the momentum equations. As in the momentum equation there are many variations for applying F, some argue that the mass flow should be corrected in either the axial equation, or both axial and tangential equations. Others have suggested a second tip loss term to account for the reduced blade forces at the tip. Below shows above momentum equations with the most common application of F.

$$F = \frac{2}{\pi} cos^{-1}\left[e^{-\left\{\frac{N\times(R-r)}{2r\,sin\varphi}\right\}}\right] \quad \cdots\cdots\cdots (3.9)$$

$$a = \frac{1}{\frac{4\,sin^2\varphi}{C_n\,\gamma} + 1} \quad \cdots\cdots\cdots (3.10)$$

$$a' = \frac{1}{\frac{4\,sin\varphi\;cos\varphi}{C_t\,\gamma} - 1} \quad \cdots\cdots\cdots (3.11)$$

The typical momentum theory applied in BEM is only effective for axial induction factors up to 0.4 (thrust coefficient of 0.96). Beyond this point the wake collapses and turbulent mixing occurs. This state is highly transient and largely unpredictable by theoretical means. Accordingly, several empirical relations have been developed. As the usual case there are several version, however a simple one that is commonly uses is a linear curve fit given below, with $a_c = 0.2$. The turbulent wake function given excludes the tip loss function, however the tip loss is applied simply by multiplying the resulting axial induction by the tip loss function.

$$C_t = 4[a_c{}^2 + (1 - 2a_c)a] \qquad when, a > a_c \qquad \cdots\cdots\cdots (3.12)$$

3.3.4 Other Methods of Aerodynamic Modeling

BEM is widely used due to its simplicity and overall accuracy. Limited success has been made with computational flow solvers based on Reynolds Averaged Navier Stokes (RANS) and other similar three-dimensional models. This is primarily due to the shear complexity modeling wind turbines. Wind turbine aerodynamics are dependent on far field conditions, several rotor diameters up and down stream, while at the same time being dependent on small scale flow conditions at the blade. Coupled with body motion, the need to have fine resolution and a large domain makes these models highly computationally intensive. For all practical purposes this approach is not worth it. As such these methods are relegated to research.

One method that is commonly applied is Biot-Savart law. The model assumes that the wind turbine rotor is shedding a continuous sheet of vortices at the tip, and sometimes the root or along the blade as in lifting line theory. Biot-Savart law is applied to determine how the circulation of these vortices induces a flow in the far field. These methods have largely confirmed much of the applicability of BEM and shed insight on the structure of wind turbine wakes. Vortex methods have limitations due to its grounding in potential flow theory, as such cannot model viscous behavior. These methods are still computationally intensive and still rely on blade element theory for the blade forces. Just like RANS, vortex methods are found solely in research environments.

3.4 Control

The control of the wind turbine is illustrated at section 2.2

3.5 Generator

For large, commercial size horizontal-axis wind turbines, the generator is mounted in a nacelle at the top of a tower, behind the hub of the turbine rotor. Typically wind turbines generate electricity through asynchronous machines that are directly connected with the electricity grid. Usually the rotational speed of the wind turbine is slower than the equivalent rotation speed of the electrical network - typical rotation speeds for a wind generators are 5-20 rpm while a directly connected machine will have an electrical speed between 750-3600 rpm. Therefore, a gearbox is inserted between the rotor hub and the generator. This also reduces the generator cost and weight.

Commercial size generators have a rotor carrying a field winding so that a rotating magnetic field is produced inside a set of windings called the stator. While the rotating field winding consumes a fraction of a percent of the generator output, adjustment of the field current allows good control over the generator output voltage. Windmills up to 3MW are now using gearless permanent magnet generators. This gives better reliability and performance than gear based systems.

Electrical generators inherently produce AC power. Older style wind generators rotate at a constant speed, to match power line frequency, which allowed the use of less costly induction generators. Newer wind turbines often turn at whatever speed generates electricity most efficiently. This can be solved using multiple technologies such as doubly fed induction generators or full-effect converters where the variable frequency current produced is converted to DC and then back to AC, matching the line frequency and voltage. Although such alternatives require costly equipment and cause power loss, the turbine can capture a significantly larger fraction of the wind energy. In some cases, especially when turbines are sited offshore, the DC energy will be transmitted from the turbine to a central (onshore) inverter for connection to the grid.

3.6 Blades

3.6.1 Blade design

The ratio between the speed of the wind and the speed the blade tips is called Tip speed ratio. High efficiency 3-blade-turbines have tip speed/wind speed ratios of 6 to 7.

Modern wind turbines are designed to spin at varying speeds (a consequence of their generator design, see above). Use of aluminum and composites in their blades has contributed to low rotational inertia, which means that newer wind turbines can accelerate quickly if the winds pick up, keeping the tip speed ratio more nearly constant. Operating closer to their optimal tip speed ratio during energetic gusts of wind allows wind turbines to improve energy capture from sudden gusts that are typical in urban settings.

In contrast, older style wind turbines were designed with heavier steel blades, which have higher inertia, and rotated at speeds governed by the AC frequency of the power lines. The high inertia buffered the changes in rotation speed and thus made power output more stable.

The speed and torque at which a wind turbine rotates must be controlled for several reasons:

- To optimize the aerodynamic efficiency of the rotor in light winds.
- To keep the generator within its speed and torque limits.
- To keep the rotor and hub within their centripetal force limits. The centripetal force from the spinning rotors increases as the square of the rotation speed, which makes this structure sensitive to over speed.
- To keep the rotor and tower within their strength limits. Because the power of the wind increases as the cube of the wind speed, turbines have to be built to survive much higher wind loads (such as gusts of wind) than those from which they can practically generate power. Since

the blades generate more downwind force (and thus put far greater stress on the tower) when they are producing torque, most wind turbines have ways of reducing torque in high winds.

- To enable maintenance; because it is dangerous to have people working on a wind turbine while it is active, it is sometimes necessary to bring a turbine to a full stop.
- To reduce noise; As a rule of thumb, the noise from a wind turbine increases with the fifth power of the relative wind speed (as seen from the moving tip of the blades). In noise-sensitive environments, the tip speed can be limited to approximately 60 m/s (200 ft/s).

3.6.2 Blade count

Figure 3.3: The NASA Mod-0 research wind turbine at Glenn Research Center's Plum Brook station in Ohio tested a one-bladed rotor configuration

The determination of the number of blades involves design considerations of aerodynamic efficiency, component costs, system reliability, and aesthetics. Noise emissions are affected by the location of the blades upwind or downwind of the tower and the speed of the rotor. Typically one bladed rotors will operate at higher tip speed ratios. Given that the noise emissions vary by the 7th power of blade speed, a small increase in speed can make a big difference.

Wind turbines developed over the last 50 years have almost universally used either two or three blades. Aerodynamic efficiency increases with number of blades but with diminishing return. Increasing the number of blades from one to two yields a six percent increase in aerodynamic efficiency, whereas increasing the blade count from two to three yields only an additional three percent in efficiency. Further increasing the blade count yields minimal improvements in aerodynamic efficiency and sacrifices too much in blade stiffness as the blades become thinner.

Component costs that are affected by blade count are primarily for materials and manufacturing of the turbine rotor and drive train. Generally, the fewer the number of blades, the lower the material and manufacturing costs will be. In addition, the fewer the number of blades, the higher the rotational speed will be. This is because blade stiffness requirements to avoid interference with the tower limit how thin the blades can be. Fewer blades with higher rotational speeds reduce peak torques in the drive train, resulting in lower gearbox and generator costs.

Figure 3.4: The 98 meter diameter, two-bladed NASA/DOE Mod-5B wind turbine was the largest operating wind turbine in the world in the early 1990s

System reliability is affected by blade count primarily through the dynamic loading of the rotor into the drive train and tower systems. While aligning the wind turbine to changes in wind direction (yawing), each blade experiences a cyclic load at its root end depending on blade position. This is true of one, two, three blades or more. However, these cyclic loads when combined together at the drive train shaft are symmetrically balanced for three blades, yielding smoother operation during turbine yaw. Turbines with one or two blades can use a pivoting teetered hub to also nearly eliminate the cyclic loads into the drive shaft and system during yawing.

Finally, aesthetics can be considered a factor in that some people find that the three-bladed rotor is more pleasing to look at than a one- or two-bladed rotor.

3.6.3 Blade materials

New generation wind turbine designs are pushing power generation from the single megawatt range to upwards of 10 megawatts. The common trend of these larger capacity designs are larger and larger turbine blades. Covering a larger area effectively increases the tip-speed ratio of a turbine at a given wind speed, thus increasing the energy extraction capability of a turbine system.

Current production wind turbine blades are manufactured as large as 80 meters in diameter with prototypes in the range of 100 to 120 meters. In 2001, an estimated 50 million kilograms of fiberglass laminate were used in wind turbine blades. New materials and manufacturing methods provide the opportunity to improve wind turbine efficiency by allowing for larger, stronger blades.

One of the most important goals when designing larger blade systems is to keep blade weight under control. Since gravity scales as the cube of the turbine radius, loading due to gravity becomes a constraining design factor for systems with larger blades.

Current manufacturing methods for blades in the 40 to 50 meter range involve various proven fiberglass composite fabrication techniques. Manufactures such as Nordex and GE Wind use a hand lay-up, open-mold, wet process for blade manufacture. Other manufacturers use variations on this technique, some including carbon and wood with fiberglass in an epoxy matrix. Options also include prepreg fiberglass and vacuum-assisted resin transfer molding. Essentially each of these options are variations on the same theme: a glass-fiber reinforced polymer composite constructed through various means with differing complexity. Perhaps the largest issue with more simplistic, open-mold, wet systems are the emissions associated with the volatile organics released into the atmosphere. Preimpregnated materials and resin infusion techniques avoid the release of volatiles by containing all reaction gases. However, these contained processes have their own challenges, namely the production of thick laminates necessary for structural components becomes more difficult. As the preform resin permeability dictates the maximum laminate thickness, bleeding is required to eliminate voids and insure proper resin distribution. A unique solution to resin distribution is the use of a partially preimpregnated fiberglass. During evacuation, the dry fabric provides a path for airflow and, once heat and pressure are applied, resin may flow into the dry region resulting in a thoroughly impregnated laminate structure.

Epoxy-based composites are of greatest interest to wind turbine manufacturers because they deliver a key combination of environmental, production, and cost advantages over other resin systems. Epoxies also improve wind turbine blade composite manufacture by allowing for shorter cure cycles, increased durability, and improved surface finish. Prepreg operations further improve cost-effective operations by reducing processing cycles, and therefore manufacturing time, over wet lay-up systems. As turbine blades are approaching 60 meters and greater, infusion techniques are becoming more prevalent as the traditional resin transfer molding injection time is too long as compared to the resin set-up time, thus limiting laminate thickness. Injection forces resin through a thicker ply stack, thus depositing the resin where in the laminate structure before gelatin occurs. Specialized epoxy resins have been developed to customize lifetimes and viscosity to tune resin performance in injection applications.

Carbon fiber-reinforced load-bearing spars have recently been identified as a cost-effective means for reducing weight and increasing stiffness. The use of carbon fibers in 60 meter turbine blades is estimated to result in a 38% reduction in total blade mass and a 14% decrease in cost as compared to a 100% fiberglass design. The use of carbon fibers has the added benefit of reducing the thickness of fiberglass laminate sections, further addressing the problems associated with resin wetting of thick lay-up sections. Wind turbine applications of carbon fiber may also benefit from the general trend of increasing use and decreasing cost of carbon fiber materials.

Smaller blades can be made from light metals such as aluminum. Wood and canvas sails were originally used on early windmills due to their low price, availability, and ease of manufacture. These materials, however, require frequent maintenance during their lifetime. Also, wood and canvas have a relatively high drag (low aerodynamic efficiency) as compared to the force they capture. For these reasons they have been mostly replaced by solid airfoils.

3.7 Tower

3.7.1 Tower height

The wind blows faster at higher altitudes because of the drag of the surface (sea or land) and the viscosity of the air. The variation in velocity with altitude, called wind shear, is most dramatic near the surface.

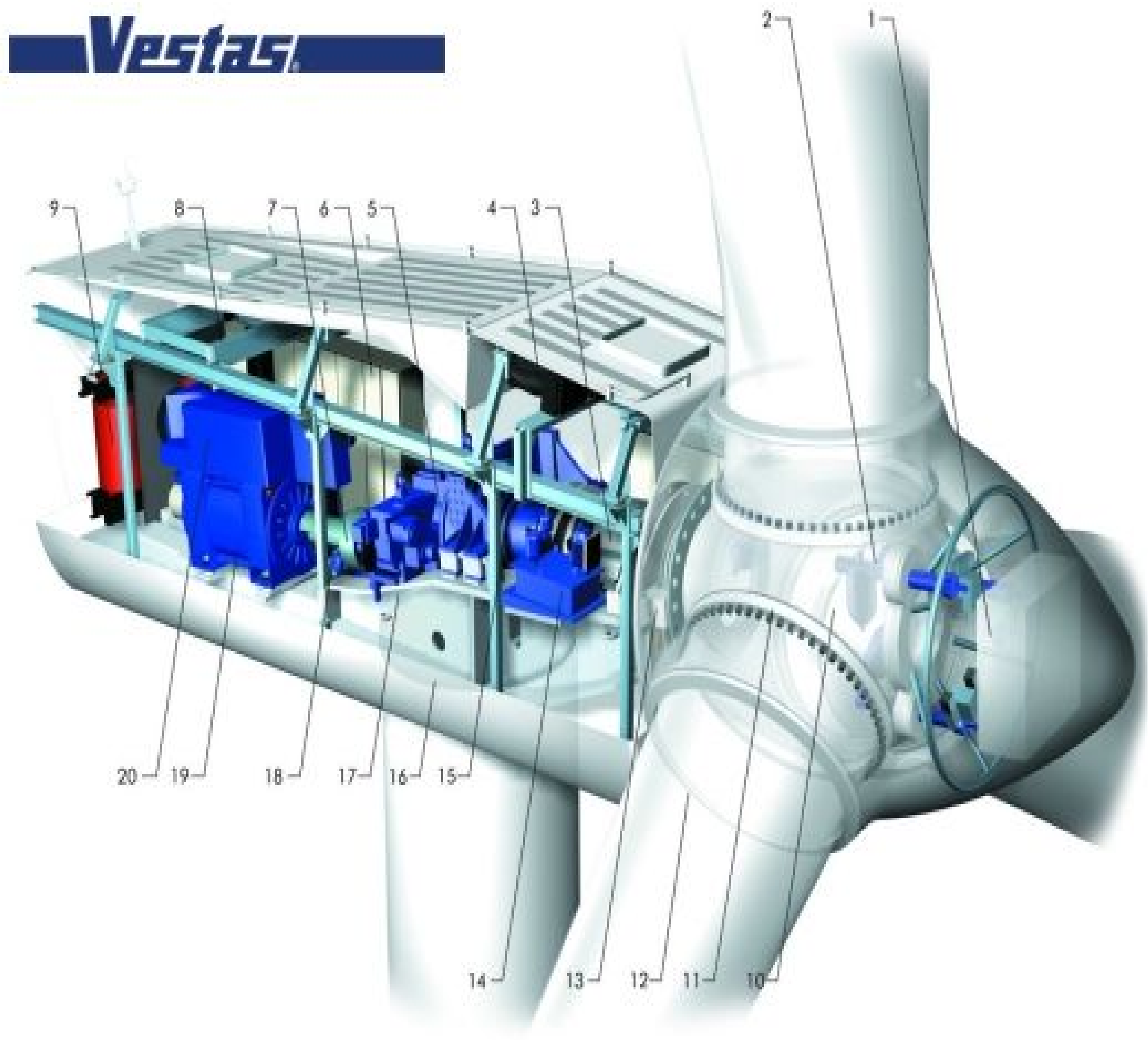
Figure 3.5: Wind turbines generating electricity at the San Gorgonio Pass Wind Farm.

Typically, in daytime the variation follows the Wind profile power law, which predicts that wind speed rises proportionally to the seventh root of altitude. Doubling the altitude of a turbine, then, increases the expected wind speeds by 10% and the expected power by 34%. To avoid buckling, doubling the tower height generally requires doubling the diameter of the tower as well, increasing the amount of material by a factor of eight.

At night time, or when the atmosphere becomes stable, wind speed close to the ground usually subsides whereas at turbine hub altitude it does not decrease that much or may even increase. As a result the wind speed is higher and a turbine will produce more power than expected from the 1/7th power law: doubling the altitude may increase wind speed by 20% to 60%. A stable atmosphere is caused by radiative cooling of the surface and is common in a temperate climate: it usually occurs when there is a (partly) clear sky at night. When the (high altitude) wind is strong (a 10-meter or 33 ft) wind speed higher than approximately 6 to 7 m/s (20-23 ft/s)) the stable atmosphere is disrupted because of friction turbulence and the atmosphere will turn neutral. A daytime atmosphere is either neutral (no net radiation; usually with strong winds and/or heavy clouding) or unstable (rising air because of ground heating — by the sun). Here again the 1/7th power law applies or is at least a good approximation of the wind profile. Indiana had been rated as having a wind capacity of 30 MW, but by raising the expected turbine height from 50 m to 70 m, the wind capacity estimate was raised to 40 MW, and could be double that at 100 m.

For HAWTs, tower heights approximately two to three times the blade length have been found to balance material costs of the tower against better utilization of the more expensive active components.

3.8 Different parts of wind turbine



1. Hub controller
2. Pitch cylinder
3. Main shaft
4. Oil cooler
5. Gearbox
6. VMP-top controller
7. Parking brake
8. Service crane
9. Transformer
10. Blade hub
11. Blade bearing
12. Blade
13. Rotor lock system
14. Hydraulic unit
15. Hydraulic shrink disk
16. Yaw ring
17. Machine foundation
18. Yaw gears
19. Generator
20. Generator cooler

Figure 3.6: Inside a wind turbine

3.8.1 The blades

Designed like airplane wings, modern wind turbine blades use lift to capture the wind's energy. Because of the blade's special shape, the wind creates a pocket of pressure as it passes behind the blade. This pressure pulls the blade, causing the turbine to rotate. This modern blade design captures the wind's energy much more efficiently than old farm windmills, which use drag, the force of the wind pushing against the blades. The blades spin at a slow rate of about 20 revolutions per minute (RPM), although the speed at the blade tip can be over 150 miles per hour.

3.8.2 Anemometer

Measures the wind speed and transmits wind speed data to the controller.

3.8.3 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.

3.8.4 Brake

A disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor on emergencies.

3.8.5 High-speed shaft

This drives the generator directly.

3.8.6 Low-speed shaft

The rotor turns the low-speed shaft at about 30 to 60 rotations per minute.

3.8.7 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.

3.8.8 The nacelle

The nacelle houses a generator and gearbox. The spinning blades are attached to the generator through a series of gears. The gears increase the rotational speed of the blades to the generator speed of over 1,500 RPM. As the generator spins, electricity is produced. Generators can be either variable or fixed speed. Variable speed generators produce electricity at a varying frequency, which must be corrected to 60 cycles per second before it is fed onto the grid. Fixed speed generators don't need to be corrected, but aren't as able to take advantage of fluctuations in wind speed.

3.8.9 The tower

The most common tower design is a white steel cylinder, about 150 to 200 feet tall and 10 feet in diameter. Some turbines use a lattice tower, like the Eiffel Tower. Towers have a ladder running up the inside and a hoist for tools and equipment.

3.8.10 The base

Bases are made of concrete reinforced with steel bars. There are two basic designs. One is a shallow flat disk, about 40 feet in diameter and three feet thick. The other is a deeper cylinder, about 15 feet in diameter and 16 feet deep.

3.8.11 Rotor

The rotor consists of the hub, three blades and a pitch regulation system, all of which are located upwind of the tower. The blades are airfoils, which depend on aerodynamic lift to move the blades and cause rotation. (Air moving over the blades creates a negative pressure on the upper side of the airfoil and a positive pressure on the lower side; this causes the rotor to rotate.) The design speed of the rotor is 16 rpm.

3.8.12 Transmission system

The mechanical power generated by the rotor blades is transmitted to the generator by the transmission system. This consists of a gearbox and a braking system plus the auxiliary lubricating and cooling systems. The gearbox is needed to increase the rotor’s speed (16 rpm) to the 1800-rpm speed of the generator. The braking system is designed to lock the rotor when shut down.

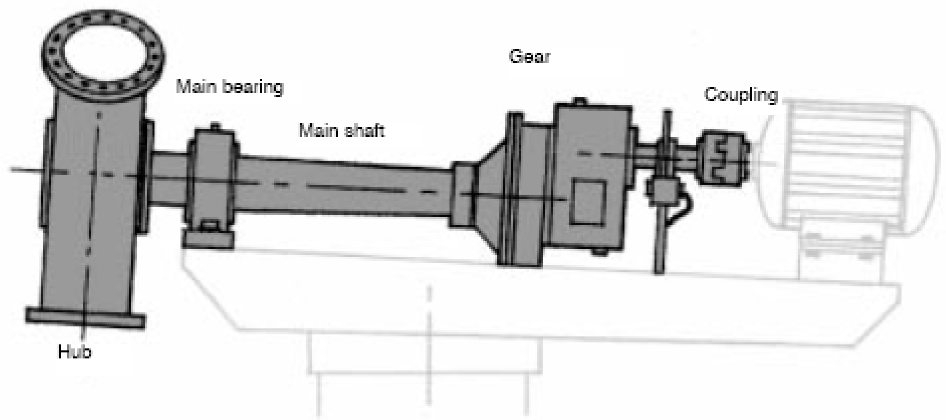


Figure 3.7: The link between the wind turbine blades and the generator

Just how much of a wind turbine that belongs to the transmission system is a matter of definition. In this chapter we will include the components that connect the wind turbine rotor to the generator.

3.8.12.1 The hub

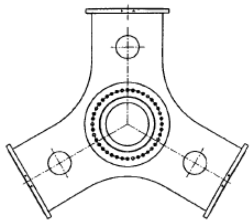


Figure 3.8: Wind turbine hub

The blades on all Bonus wind turbines are bolted to the hub. Older Bonus wind turbines (up to and including the 95 kW models) with Aerostar blades, have a flange joint, where the glass fiber is molded out in a ring with steel bushes for the bolts. The newer wind turbines (from the 150 kW models) have threaded bushes glued into the blade root itself. In the both cases bolts from the blade pass through a flange on the cast hub. The flange bolt-holes are elongated, enabling the blade tip angle to be adjusted.
The hub is cast in a special type of strong iron alloy, called 'SG cast iron'. Because of the complicated hub shape which is difficult to make in any other way, it is convenient to use cast iron. In addition the hub must be highly resistant to metal fatigue, and this is difficult to achieve in a welded construction.
In contrast to cast iron of the SG type, normal cast iron has the disadvantage of being rather fragile and often can fracture under blows. This unfortunate quality is due to the high carbon content of cast iron. High carbon content enables the cast iron to melt easily and thus easily flow out into the casting form. When cast iron solidifies, carbon exists as graphite flakes suspended in the pure iron. These flakes form weak zones in the material, easily prone to zigzag fissures from flake to flake. These weak zones are only important, if forces attempt to pull the material apart. Graphite has great compressibility strength, and is therefore not easily compressed. Normal cast iron has the same compressibility strength as steel, but its tension resistance level is only 10% of steel tension resistance.
For many uses these strength qualities are more than sufficient, however in constructions subject to heavy usage, properties such as low tension resistance and weakness under blows are not desirable. For this reason special SG cast iron with tension resistance equal to that of steel has been developed during the past 50 years.
In producing SG cast iron several special materials, mainly silicium, are added during casting. After casting has taken place, it is further heat treated for about 24 hours, thereby changing the free carbon from their usual flakes into small round balls. The name SG cast iron is also short for Spherical Graphite cast iron (Latin: Sphere = ball).
This round ball shape binds the necessary carbon in a more compact form. The graphite is not a hindrance for the binding structure in the metal itself, and there is likewise a better structure between the crystals of iron. Thereby achieving the higher strength qualities necessary for a wind turbine hub. On account of the extra heat treatment, SG cast iron is somewhat more expensive than normal cast iron.

3.8.12.2 Main shaft

The main shaft of a wind turbine is usually forged from hardened and tempered steel. Hardening and tempering is a result of forging the axle after it has been heated until it is white-hot at about 1000 degrees centigrade. By hammering or rolling the blank is formed with an integral flange, to which the hub is later bolted.

The shaft is reheated a final time to a glowing red, following the forging process, and then plunged into a basin of oil or water. This treatment gives a very hard, but at the same time rather brittle surface.

Therefore the axle is once again reheated to about 500 degrees centigrade, tempering the metal and thereby enabling the metal to regain some of its former strength.

3.8.12.3 Main bearings

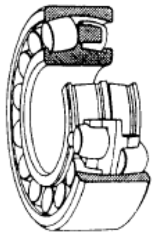


Figure 3.9: Spherical roller bearing (Niemen)

All modern wind turbines, including the Bonus models, have spherical roller bearings as main bearings. The term spherical means that the inside of the bearing's outer ring is shaped like a cross section of a ball. This has the advantage of allowing the bearing's inner and outer ring to be slightly slanted and out-of track in relation to each other without damaging the bearing while running. The maximum allowable oblique angle is normally 1/2 degree, not so large, but large enough to ensure that any possible small errors in alignment between the wind turbine shaft and the bearing housing will not give excessive edge loads, resulting in possible damage to the bearing.

The spherical bearing has two sets of rollers, allowing both absorption of radial loads (across the shaft) from the weight of the rotor, shaft, etc. and the large axial forces (along the shaft) resulting from the wind pressure on the rotor.

The main bearings are mounted in the bearing housings bolted to the main frame. The quantity of bearings and bearing seats vary among the different types of wind turbines: 'Small' wind turbines up to and including 150 kW have two bearings, each with its own flanged bearing housing. The 250/300 kW wind turbines have only one main bearing, with the gearbox functioning as a second main bearing. The 450 kW, 500 kW and 600 kW wind turbine models have two main bearings, using the hub as housing. Each bearing arrangement has advantages and disadvantages, and the evaluation of these properties have provides each individual type with its own setup.

The main bearings are always lubricated by greasing, no matter which bearing arrangement is selected. Special grease having viscose properties even in hard frost is used.

Sealing of the bearing housing is insured by the use of a labyrinth packing. No rubber sealing is used; the labyrinth with its long and narrow passageway prevents grease from escaping. Water and dirt are prevented from entering from the outside by the long passageways filled with grease, which is constantly and slowly trying to escape from the bearing. This may appear to be a rather primitive arrangement, but labyrinth packing is a much used method where there is great risk of pollution by water and dirt. It is more expensive to use than a rubber sealing, because the labyrinth is complicated to fabricate on machine tools, however the seal is not subject to wear, and under normal conditions it is a safe method to keep out the pollutants that otherwise in a short time could ruin roller bearings.

3.8.12.4 The clamping unit

By the means of a clamping unit the main shaft of the wind turbine is coupled to the gearbox. The gear has a hollow shaft that fits over the rear end of the main shaft. Torque between the two components is transferred by friction between the two.

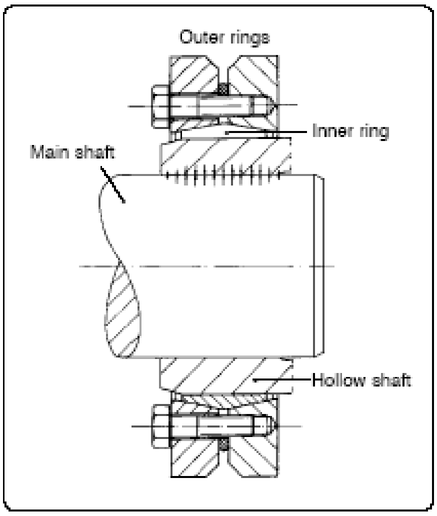


Figure 3.10: Clamping unit (TAS Sh.fer)

A clamping unit, normally composed of an inner ring and two outer rings with conical facings, is placed on the outside of the gear's hollow shaft. When the main shaft is placed inside the hollow shaft during the assembly of the wind turbine, the conical facings of the clamping unit are loosely positioned on the hollow shaft. Following control of the correct alignment of the gear and the main shaft, the rings are tightened by the means of a large number of bolts. The outer rings are thereby pressed together, while the inner ring, positioned on the hollow shaft is pressed inwards under the tightening of the bolts. The inner ring now presses so hard against the hollow shaft that the inner part of the hollow shaft is in turn pressed hard against the main shaft. It is because of this pressure that the torque is transferred from the main shaft to the wind turbine gear hollow shaft. One might also say that the hollow shaft is shrink-fitted on the main shaft as a result of pressure from the clamping unit.

Transferred torque is dependent upon friction between the main shaft and the hollow shaft. Therefore it is vital that the components are carefully cleaned and completely dry, before they are assembled. If they are at all greasy, they could slip in relation to each other during high loads, for example during the cut-in process in strong wind conditions.

Many know of the parallel key method, often used in assembling a shaft to a hub. The main shaft's torque is transferred by forces across the parallel key (a parallel key is often called a wedge, even though it is not wedge shaped). This assembly method is not often used with a large shaft, there being too great a risk that in time the different parts could loosen, unless they fit uncommonly well together. If the parallel key junction assembly method is used for large shafts, parts must fit so well together, that in practice one is unable to dismantle them in the field, should it be necessary during possible replacement in case of damage or repair.

3.8.12.5 The gearbox

One of the most important main components in the wind turbine is the gearbox. Placed between the main shaft and the generator, its task is to increase the slow rotational speed of the rotor blades to the generator rotation speed of 1000 or 1500 revolutions per minute (rpm).

Without much previous experience with wind turbines, one might think that the gearbox could be used to change speed, just like a normal car gearbox. However this is not the case with a gearbox in a wind turbine.

In this case the gearbox has always a constant and a speed increasing ratio, so that if a wind turbine has different operational speeds, it is because it has two different sized generators, each with its own different speed of rotation (or one generator with two different stator windings).

As an example of a gearbox construction, we can study a Flender SZAK 1380 gear for a 150 kW wind turbine.

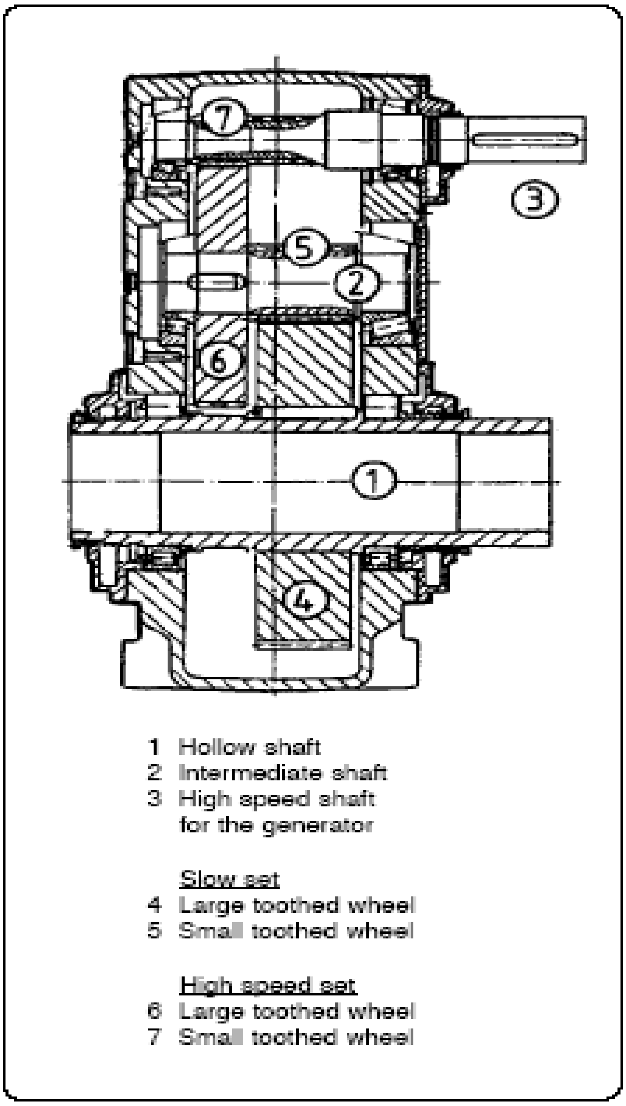


Figure 3.11: Flender SZAK 1380 2-trins gear

This gear has two sets of toothed gear wheels, a slow speed stage and a high speed stage. In the slow speed stage the large gear wheel is mounted directly on the gear's hollow shaft, while the smaller gear wheel is machined directly on the intermediate shaft.

The difference in the size of the wheels is 1:5. The intermediate shaft therefore turns 5 times every time the hollow shaft makes one complete revolution. The large gear wheel in the high speed gear stage is also mounted on the intermediate shaft, while the small gear wheel in the high speed gear stage is machined on the generator shaft itself. Here the difference in size is also about 1:5, so that the output shaft to the generator shaft turns 5 times for every one rotation of the intermediate shaft.

When the two ratios are combined, the output shaft will turn 25 times for every rotation of the hollow shaft and the main shaft of the wind turbine combined one can say that the gear has a gear ratio of 1:25.

Normally the ratio in every set of gear wheels is restricted to about less than 1:6. The 150 kW wind turbine has a rotor rotational speed of 40 rpm and with a generator speed of about 1000 rpm, the gearbox must have a total gear ratio of 40/1000 or 1:25. This is possible using a two stage gearbox. A 300 kW wind turbine has a rotor rotational speed of 31 rpm and a generator with a rotational speed of 1500 rpm. It therefore requires a gearbox with a gearbox ratio of 31/1500 or 1:48. This is not possible using a gearbox with only two stages, so the 300 kW wind turbine gearbox has an extra intermediate shaft, giving in all a three stage gearbox.

Wind turbines, from 450 kW and larger, have an integrated gearbox with a planet gear and two normal stages.

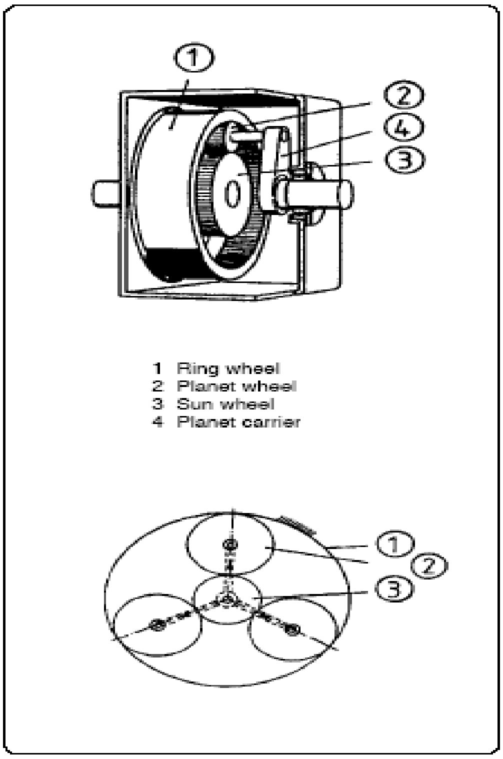


Figure 3.12: Planet gear */DIN 686/Niemen

The planet gear is a special version of the toothed gear. This type of gear is of great delight to gearbox technicians, as it can be combined in countless different complicated variations, each one carefully calculated with its own special inner logic. The form of planet gear used on wind turbines is however always of the same basic design: An interior toothed gear wheel (ring wheel), three smaller toothed gear wheels (planet wheels) carried on a common carrier arm (the planet carrier) and finally a centrally placed toothed gear wheel (the sun gear wheel). It is this construction, with three smaller gear wheels orbiting a centrally placed common gear wheel that has given this type of gear its name of planet gearbox.

The ring wheel itself is stationary, while the planet carrier is mounted on the hollow shaft. When the planet carrier rotates with the same rotational speed as the rotor blades, the three planet wheels turn around inside the inner circumference of the ring wheel and thereby also greatly increase the rotational speed of the centrally placed sun gear wheel. One can usually obtain a gear ratio of up to about 1:5. The sun gear wheel is fixed to a shaft driving the two normal gear stages placed at the rear end of the gearbox.

The fact that there are always three gear wheels supporting each other and that all gear wheels are engaged at the same time, is one of the advantages of the planet gear. This means that it is possible to construct rather compact planet gearboxes, because the larger ring wheel does not need to be as large as a gear wheel in a traditional type of gearbox. In principle it only needs to be about a 1/3 of the size. However in reality it not quite so simple. If a gear is needed to transfer heavy loads, it is often somewhat cheaper to use a planet gear.

However it is in the very nature of things that trees do not grow up into heaven, and also planet gears have their own special disadvantages. The compact construction, very practical for the design and construction of the rest of the machine can be in itself a disadvantage. The compact construction makes it difficult to effectively dissipate excess heat to the surroundings. A gear is not 100% effective, and as a rule of thumb it is estimated that roughly 1% of the power is lost at each stage. A 600 kW gearbox running at full capacity, must therefore dispose of about 18 kW of waste heat. This is equivalent to nine normal household hot air blower-heaters operating at full blast. This waste heat should preferably be radiated by surface cooling and of course the less gearbox surface area, the higher the temperature must be inside the gearbox to transfer the necessary, unavoidable excess waste heat.

Another disadvantage of the planet gear is that they normally cannot be constructed with beveled machined teeth. Beveled teeth are always used in normal gearboxes in order to reduce the noise level. When the teeth are set at an angle, the next tooth will start to engage and take up the load before the previous tooth has slipped contact. This results in a quieter, more harmonious operation. For interior gear wheels beveled teeth can only be machined using special machine tools that up until now have solely been used for the machining of very large turbine gears for use in ships. Therefore planet gears have always straight machined teeth, unfortunately however, resulting in a higher noise level. By combining a planet gear stage and two normal gear stages, one obtains an acceptable compromise of the advantages and disadvantages with the two different types of gear.

No matter what type of gear is used, the shape of the teeth in the different gear stages is adapted to the special conditions for wind turbine operation, especially those that are related to the noise level. Teeth as a rule are case-hardened and polished. Case-hardening is a method of giving surface strength to a specific material. During this process, the inner material maintains its previous strength, which can often be lost in normal steel hardening processes.

Hardening can only take place under conditions where there is a carbon content in the steel. The gear wheels are made of special low carbon chrome-nickel steel. The teeth are first machined, and following the machining process, the gear wheels are packed into large boxes full of bone flour or some other form of high carbon-content powder. The boxes are placed in an oven and heated for about 24 hours to a red glowing temperature. During this baking process some of the free carbon will be transferred from the surrounding carbon-rich powder in the boxes to the gear wheel teeth surfaces. This is described as the method of hardening the teeth in boxes or cases, and therefore from this process comes the descriptive name of case-hardening.

The increased carbon content of the teeth surface allows the top edges of the gear wheel teeth to become harder, so following case hardening, the gear wheel is lifted out, still red hot, and lowered into an oil bath. This completes the process of hardening, and the gear wheel now has a hardened surface, while the inner material still has ductile and not hardened properties. The hardening process slightly deforms the material, so it is necessary to finish the process by grinding.

3.8.12.6 The coupling

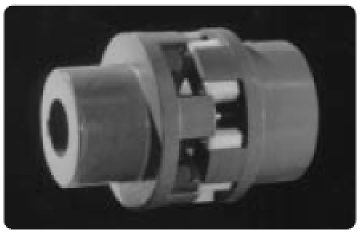


Figure 3.13: Coupling (Flender BIPEX)

The coupling is placed between the gearbox and the generator. Once again it is not possible to consider the coupling as the same as a clutch in a normal car. One cannot engage or disengage the transmission between the gearbox and the generator by pressing a pedal, or in some other such way. The transmission is a permanent union, and the expression ‘coupling’ should be understood as a junction made by a separate machine component.

The coupling is always a ‘flexible’ unit, made from built-in pieces of rubber, normally allowing variations of a few millimeters only. This flexibility allows for some slight differences in alignment between the generator and the gearbox. This can be of importance under assembly and also during running operation, when both gearbox and generator can have tendencies for slight movement in relation to each other.

3.8.13 Generator

The generator converts the mechanical energy to electrical energy in an asynchronous (induction) generator.

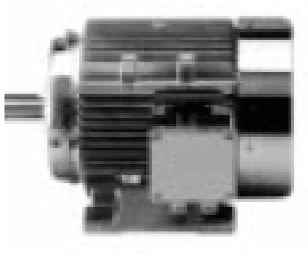


Figure 3.14: The wind turbine electrical system

The generator is the unit of the wind turbine that transforms mechanical energy into electrical energy. The blades transfer the kinetic energy from the wind into rotational energy in the transmission system, and the generator is the next step in the supply of energy from the wind turbine to the electrical grid.

In order to understand how a generator works, it is necessary to first of all understand the deeper principles in the electrical system to which the generator is connected. Therefore we will first discuss the electrical systems based on Direct Current (DC) and those based on Alternating Current (AC).

3.8.13.1 Induction and electromagnetism

Before finally describing the generator itself, we must briefly explain a couple of the basic principles of electromagnetism.

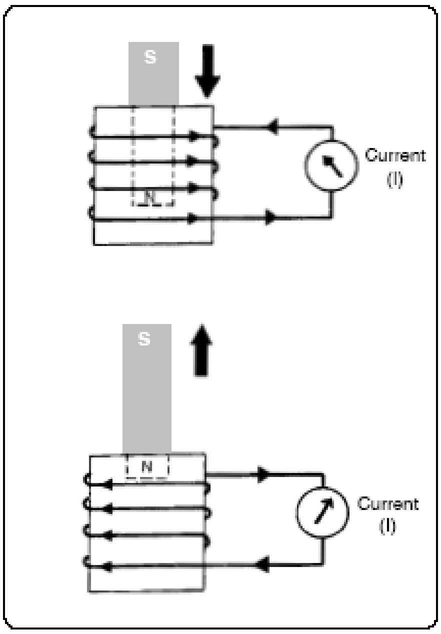


Figure 3.15: The principles of induction

If the magnet is stuck inside the coil, an electric current is registered in the coil circuit. If the magnet is withdrawn, a current of the same strength is registered, but in the opposite direction. The faster the changes of the magnetic field in the coil, the greater the current. The same occurs if instead of the magnet being stuck into the open coil it is merely moved past one of the ends of the coil. The effect is especially powerful if the coil has an iron core.

One can say that alterations in the magnetic field, induce a current in the coil, and the phenomena is known as induction.

In just the same way that a magnetic field can bring about an electric current, so can an electric current likewise cause a magnetic field to be created. Electromagnetism was first demonstrated by the Danish scientist H.C ørsted in his famous experiment, where an electrical current was able to turn a compass needle. He had therefore demonstrated the first electromagnet.

In practice a good electromagnet is best made as a coil with an iron core, in just the same way as the previously mentioned form of coil that produces an electric current when a magnet is moved past at a close distance. Like a permanent magnet an electromagnet has two poles, a north pole and a south pole. The position of these two poles depends on the direction of the flow of electrical current.

3.8.13.2 The wind turbine generator as a motor

The asynchronous generator we will describe here is the most common type of generator used in Danish wind turbines. It is often referred to as the induction generator, too. As far as we know the asynchronous generator was first used in Denmark by Johannes Juul, known for the 200 kW Gedser wind turbine from 1957. Already some years prior to this construction he erected a 13 kW experimental wind turbine with an asynchronous generator at Vester Egesborg in the south of the large Danish island of Zeeland.

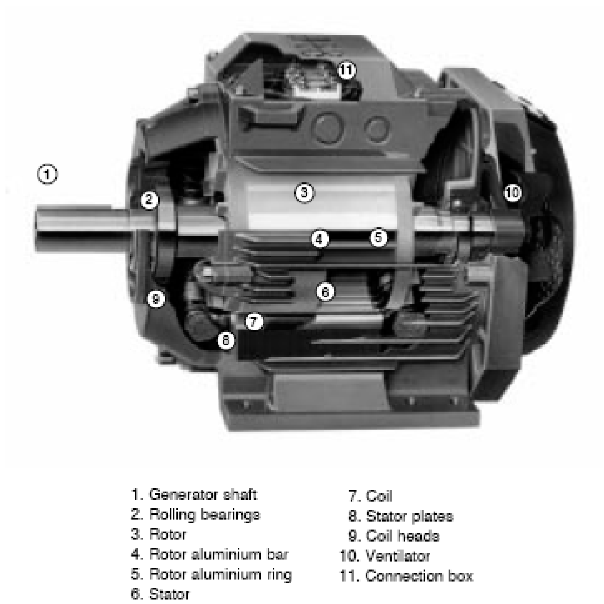


Figure 3.16: Components of an asynchronous motor

The asynchronous generator is in reality a type of motor that can also operate as a generator, and we will first consider this type as a motor. This is the most common electric motor, sitting in almost every washing machine, and widely used as a motor unit in industry.

The motor consists of two main parts, the stator and the rotor. The stator contains a series of coils, the number of which must be divisible by three. The motor illustrated on this page has six coils, placed in slots on the inside of the stator, a cylinder assembled of thin iron plates. The rotor sits on an axle placed inside this stator. The rotor is also assembled of thin iron plates. A row of thick aluminum bars joined at each end with an aluminum ring fit in key ways on the outer surface of the rotor. This rotor construction looks a bit like a squirrel cage, and accordingly the asynchronous motor is also called a squirrel cage motor.

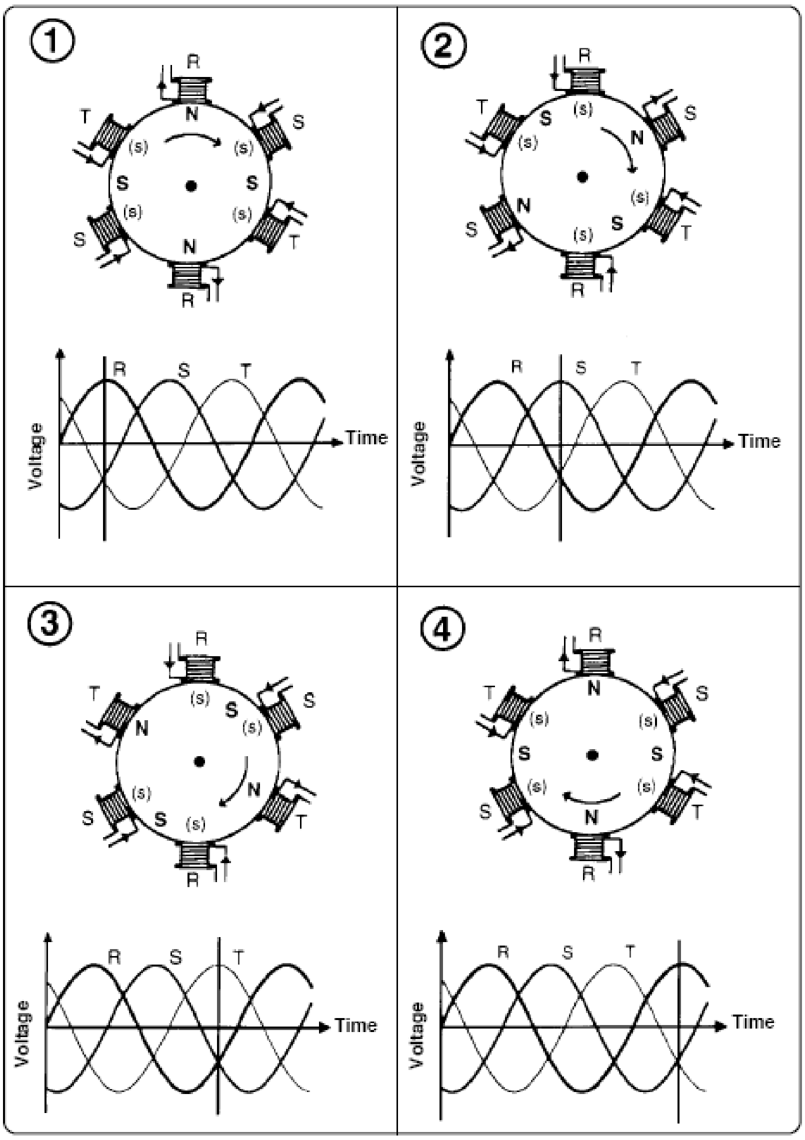


Figure 3.17: 4 situations of the rotation magnetic field

The six coils in the stator are connected together, two by two to the three different phases of the electrical grid. This arrangement insures that there is a rotating magnetic field inside the stator itself. This is best illustrated by the above diagram.

At a specific time ‘1’ the current in phase R is at its maximum, and this produces a magnetic field with a strong north pole at both the opposite coils connected to the phase R. At phase S and phase T the current is somewhat under zero, and the two pairs of coils produce a medium strength South Pole, producing a powerful south pole halfway between the two coils.

At time ‘2’ the current at phase S is at a maximum and the North Pole is now at the two opposing coils connected to this phase. The current at phases R and T is likewise reduced to less than zero, and the South Pole is now between these two coils.

At time ‘3’ the current at phase T now is at a maximum, and the North Pole is at the two coils connected to phase T. The South Pole has also turned, and is now halfway between the coils connected to phases R and S.

At time ‘4’ the situation has now returned to as it was at the start of the electrical current rotation, with the north poles at the end of the coils connected to phase R.

In one complete cycle, from the current peak to the next following peak, the magnetic field has rotated through half a circle. There are 50 cycles per second, so the field turns at 25 times per second, or 60 x 25 = 1.500 rpm (revolutions per minute).

To understand how a generator works, it is easiest to first consider two different situations where a generator operates as a motor, at 0 rpm. and at 1.500 rpm.

In the first case the rotor is stationary, while the stator turns at 1.500 rpm. The coils in the rotor experience rapid variations of a powerful magnetic field. A powerful current is thereby induced in the short circuited rotor wire windings. This induced current produces an intense magnetic field around the rotor. The North Pole in this magnetic field is attracted by the South Pole in the stator's turning magnetic field (and of course, the other way round) and this will give the rotor a torque in the same direction as the moving magnetic field. Therefore the rotor will start turning.

In the second situation, the rotor is turning at the same speed as the stator magnetic field of 1.500 rpm. This rotational figure is called the synchronous rotational speed. When the stator magnetic field and the rotor are synchronized, the rotor coils will not experience variations in the magnetic field, and therefore current will not be induced in the short circuited rotor windings. Without induced current in the rotor, there will be no magnetic field in the rotor windings and the torque will be zero.

On account of bearing friction the motor must produce a little torque to keep rotating, and therefore cannot run at exactly the same speed as the rotating magnetic field. As soon as the speed slows down, there will be a difference between the speed of the rotating magnetic field and the rotor. The rotor thus again experiences a variation in the magnetic field that induces a current in the rotor windings. This current then produces a magnetic field in the rotor, and the rotor can produce a torque.

During motor operation, the stator experiences a constantly changing magnetic field, being dragged round by its rotating magnetic field. During this process, electrical current is induced in the stator, which results in a power consumption. In fact, the slower the rotor turns in relation to the rotating magnetic field of the stator, the stronger the induction in the stator, and therefore the greater the power consumption.

The fact that the rotor has no torque at the precise synchronous rotational speed and therefore will always run slightly slower has given this motor type its name, the asynchronous motor.

3.8.13.3 Generator operation

As we have previously mentioned, the asynchronous motor can also run as a generator. This simply happens when you, instead of forcing the rotor to turn at a rotational speed lower than the synchronous speed, exceed this synchronous speed by applying an outside energy source, such as a diesel motor or a set of wind turbine rotor blades.

Once again, the greater the difference between the rotating magnetic field of the stator (which is always 1.500 rpm) and the speed of the rotor, the greater the torque produced by the rotor. When a working as a generator, the rotating field however acts as a brake in slowing the rotor. The stator experiences a variable magnetic field from the rotor that 'drags' its rotating magnetic field and thereby induces an electrical current in the stator. In comparison to motor operation the induced currents in the rotor and stator will flow in the opposite direction, which means that power will be sent to the grid. The faster the rotor turns in relation to the rotating magnetic field of the stator, the greater the induction in the stator and the greater the production of power.

In practice the difference between the speed of rotational magnetic field of the stator and the rotational speed of the rotor is very little. A rotor will typically turn about 1% faster at full power production. If the synchronous rotational speed is 1.500 rpm then the rotor rotational speed at full power will be 1.515 rpm.

The interesting torque curve of the asynchronous electric motor, also operating as a generator, is shown below. At speeds below the synchronous rotational speed, the motor yields a positive torque.

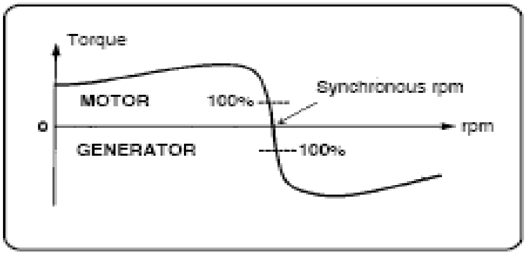


Figure 3.18: Torque curve

Typically a maximum torque of about 2.5 times the torque of the nominal power. If the rotational speed exceeds the synchronous level, the torque becomes negative, and the generator acts as a brake.

At the Bonus factory, we have a rather interesting apparatus that demonstrates this shift between a motor and generator. A small asynchronous motor is connected to an electric meter. The motor has a gearbox giving a shaft speed of 60 rpm.

A small crank handle is fixed to the shaft. The motor starts when it is plugged into a normal mains socket coming from the electrical grid and consumes a small amount of electrical energy due to friction loss in the motor and gearbox.

If one attempts to resist the rotation of the shaft by holding back the crank, the consumption of energy will increase. If the crank however is used to increase the speed of the motor, then the electric meter will start to run backwards, showing that current is flowing the other way. In this way one can, by using human muscle power, feed electrical power to the grid, in just the same way that a wind turbine feeds power to the grid. It is difficult to achieve more than 1/20 kW so a work force of twelve thousand employees is needed to compete with one single 600 kW wind turbine operating in a good wind. Visitors to Bonus may try their hand at our generator demonstration model.

3.8.13.4 Cut-in

If a wind turbine is connected to the grid during a period of no wind, the asynchronous generator will operate as a motor and drag the rotor blades round like a large electric fan. The wind turbine therefore is disconnected from the grid during periods of calm.

The wind turbine is likewise disconnected during periods of low wind speeds, allowing the blades to slowly rotate. The control system of the wind turbine however constantly monitors the rotational speed, and after the blades reach a certain pre-set level, the system permits a gradual cut-in to the grid.

The cut-in to the grid is carried out by the use of a kind of electronic contacts called thyristors, allowing continuously variable up and down regulation of the electrical current. Such thyristors allow smoother and gentler generator cut-in, thus preventing sudden surges of current causing possible grid damage. Likewise this gentler switching procedure prevents stress forces in the gearbox and in other mechanical components. A direct cut-in, using a much larger electrical switching unit result in violent shock-effects, not only to the grid but also to the whole transmission system of the wind turbine itself.

Unfortunately, thyristors have the disadvantage of an power loss of about 1-2%, so after the finish of the cut-in phase, current is led past the thyristors direct to the grid by the means of a so-called ‘by-pass switch’.

3.8.13.5 Closing remarks

It has been necessary to make many simplifications in the above description. We have considered such important terms, as self-induction, reactive current and phase compensation to be too complicated in a more general description such as this. During the induction process, in reality it is not an electric current that is created, but an electromotive force giving rise to a certain current dependent upon the resistance.

We have used the rotational speed for a 4-pole and 6 coil generators (3 x 2). In the diagram showing the rotating field, one can observe that there are 2 north poles and 2 south poles, 4 in all. Other generators may have 9 coils, which would mean 3 north poles and 3 south poles. Such a 6 pole generator has a synchronous rotational speed of 1.000 rpm.

Bonus wind turbines up to and including the 150 kW models has 6 pole generators, while the larger models have 4 pole generators.

3.8.14 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.

3.8.15 Wind vane

Measures wind direction and communicate with the yaw drive to orient the turbine properly with respect to the wind.

3.8.16 Yaw drive

The yaw system turns the nacelle into the actual wind direction using a rotary actuator and a gear mechanism at the top of the tower. 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. A fully automatic microprocessor-based control and monitoring system is a part of the wind turbine. The control system is designed for remote operation from the shore-based operations center via a fiber optic communications system.

3.9 Comparison of parts for different size wind turbine

The following table will show the comparison of parts between small and big wind turbines.

Table 3.1: Parts comparison of different size wind turbine

Parts for small wind turbine	Parts for big wind turbine
i. Blades	i. Blades
ii. Hub	ii. Blade bearing
iii. DC motor (i.e. permanent magnet motor).	iii. Blade hub
	iv. Hydraulic unit
	v. Hub controller
iv. Diode	vi. Gearbox
v. Mount	vii. Generator
vi. Wires	viii. Main shaft
vii. Tail	ix. Yaw ring
viii. Tower Base	x. Yaw gears
ix. Tower pole	xi. Brakes
x. Tower guy wires	xii. Tower
	xiii. Tower base
	xiv. Transformer
	xv. Controller

4

Sample design

4.1 The Power of Wind

Because air has mass and it moves to form wind, it has kinetic energy. You may remember from science class that:

$$Kinetic\ energy\ (Joules) = \frac{1}{2} mU^2 \qquad \cdots\cdots\cdots (4.1)$$

Where,

m = mass (kg) (1 kg = 2.2 pounds)
U = velocity (meters/second) (meter = 3.281 feet = 39.37 inches)

Usually, we're more interested in power (which changes moment to moment) than energy. Since energy = power x time and density is a more convenient way to express the mass of flowing air, the kinetic energy equation can be converted into a flow equation.

Power in the area swept by the wind turbine rotor,

$$P_e = \frac{1}{2} \times \rho \times C_p \times A \times U^3 \qquad \cdots\cdots\cdots (4.2)$$

Where,

P_e = power extracted by the rotor in watts (746 watts = 1 hp) (1,000 watts = 1 kilowatt)
ρ = air density (about 1.225 kg/m^3 at sea level, less higher up)
A = rotor swept area, exposed to the wind (m^2)
C_p = power coefficient
U = wind speed in meters/sec (20 mph = 9 m/s) (mph/2.24 = m/s)

This yields the power in a free flowing stream of wind. Of course, it is impossible to extract all the power from the wind because some flow must be maintained through the rotor (otherwise a brick wall would be a 100% efficient wind power extractor). So, we need to include some additional terms to get a practical equation for a wind turbine power,

$$P = P_e \times N_g \times N_b \qquad \cdots\cdots\cdots (4.3)$$

$$\Rightarrow P = \frac{1}{2} \times \rho \times A \times C_p \times U^3 \times N_g \times N_b \qquad \cdots\cdots\cdots (4.4)$$

Where,

P= actual power in watts (746 watts = 1 hp) (1,000 watts = 1 kilowatt)
ρ= air density (about 1.225 kg/m^3 at sea level, less higher up)
A= rotor swept area, exposed to the wind (m^2)
C_p = power coefficient
U = wind speed in meters/sec (20 mph = 9 m/s)
N_g = transmission efficiency from the rotor to the generator i.e., generator efficiency (50% for car alternator, 80% or possibly more for a permanent magnet generator or grid-connected induction generator)
N_b = energy conversion efficiency of the generator i.e., gearbox/bearings efficiency (depends, could be as high as 95% if good)

4.2 Performance calculation

The power coefficient (C_p) of a wind machine is the ration of the power extracted by the rotor to the power available in the wind stream.

$$C_p = \frac{P_e}{\frac{1}{2}\rho A U^3} \qquad \cdots\cdots\cdots (4.5)$$

Where,

P_e = power extracted by the rotor in watts (746 watts = 1 hp) (1,000 watts = 1 kilowatt)
ρ = air density (about 1.225 kg/m^3 at sea level, less higher up)
$A = \pi R^2$= rotor swept area, exposed to the wind (m^2)
C_p = power coefficient
U = wind speed in meters/sec (20 mph = 9 m/s) (mph/2.24 = m/s)

The tip speed ratio (λ) is the ration of the speed of the blade tip to the free stream wind speed,

$$\lambda = \frac{\omega R}{U} \qquad \cdots\cdots\cdots (4.6)$$

Where,

ω = Angular velocity in rad/s
R = Radius of the rotor or tip radius in meter

This definition holds for a horizontal axis machine. For a vertical axis machine, the peripheral speed at the middle of the blade length is used in the numerator instead of the speed of the blade tip.

The solidity (γ) of a wind machine is the ratio of the blade area to the swept frontal area (face area) of the machine. This definition holds for a horizontal axis machine and the following expression is obtained under the assumption that the blade length is equal to the tip radius,

$$\gamma = \frac{N\,c}{\pi\,R} \qquad \ldots\ldots\ldots (4.7)$$

$$\Rightarrow \gamma = \frac{N\,c\,l}{\pi\,R^2} \qquad [\because l \simeq R] \qquad \ldots\ldots\ldots (4.8)$$

Where,

N= number of blades
c= mean chord of the blades in meters
l= lengths of the blades in meters
R= radius of the rotor

For a vertical axis machine, the expression 4.6 is (Nc/R) used for the Darrieus type and $(Nc/2R)$ for others types.

4.3 Betz Limit

4.3.1 Understand the Betz Limit and how it affects wind turbines

Albert Betz was a German physicist who in 1919 concluded that no wind turbine can convert more than 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy turning a rotor. To this day this is known as the Betz Limit or Betz' Law. This limit has nothing to do with inefficiencies in the generator, but in the very nature of wind turbines themselves.

Wind turbines extract energy by slowing down the wind. For a wind turbine to be 100% efficient it would need to stop 100% of the wind - but then the rotor would have to be a solid disk and it would not turn and no kinetic energy would be converted. On the other extreme, if we had a wind turbine with just one rotor blade, most of the wind passing through the area swept by the turbine blade would miss the blade completely and so the kinetic energy would be kept by the wind.

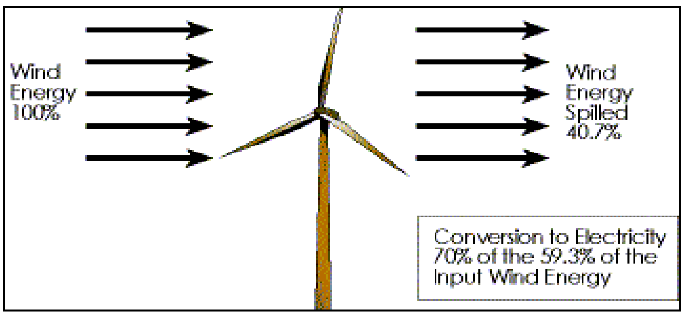


Figure 4.1: Effective wind energy efficiency for a wind turbine

4.3.2 Real World Wind Turbine Power Efficiencies

The theoretical maximum power efficiency of any design of wind turbine is 0.59 (i.e. no more than 59% of the energy carried by the wind can be extracted by a wind turbine). Once you also factor in the engineering requirements of a wind turbine - strength and durability in particular - the real world limit is well below the Betz Limit with values of 0.35-0.45 common even in the best designed wind turbines. By the time you take into account other ineffiencies in a complete wind turbine system - e.g. the generator, bearings, and power transmission and so on - only 10-30% of the power of the wind is ever actually converted into usable electricity.

Horizontal axis wind turbines (HAWT) theoretically have higher power efficiencies than vertical axis wind turbines (1) (VAWT) however wind direction is not important for a VAWT and so no time (and power) is wasted chasing the wind. In turbulent conditions with rapid changes in wind direction more electricity will be generated by a VAWT despite its lower efficiency.

4.4 Different types of rotor's performance curve

The variation of power coefficient with tip speed ratio has been obtained both theoretically and experimentally for many horizontal and vertical axis rotors. Some typical results are shown in the following figure,

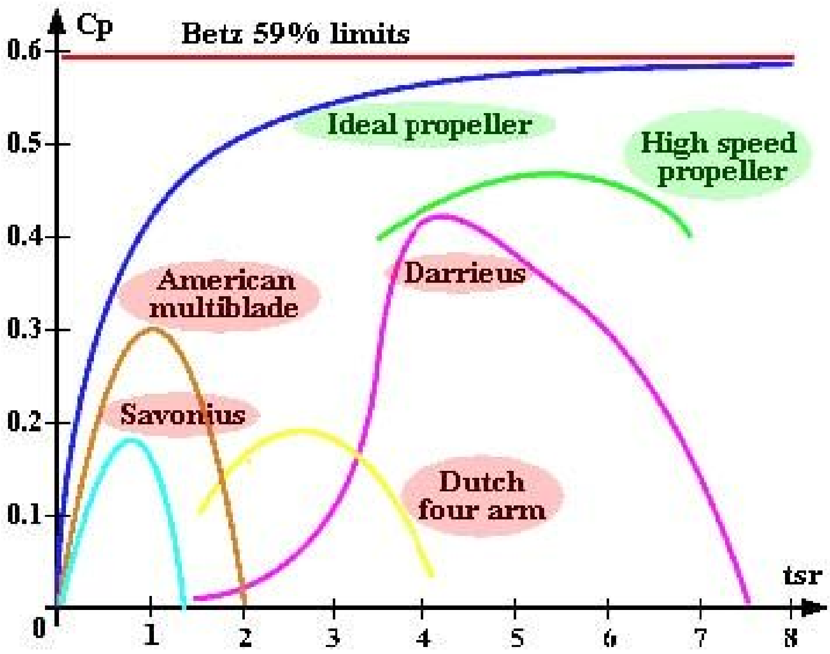


Figure 4.2: Variation of power coefficient (C_p) with tip speed ratio (λ) for various types of rotors.

The data in figure 4.2 can be used for calculating the performance of a given machine or for designing the rotor for a specified performance.

Note: High speed propeller in figure 4.2 means one, two or three bladed HAWT type turbines.

The variation of solidity with tip speed ratio ideal curve for all type of rotors is given bellow,

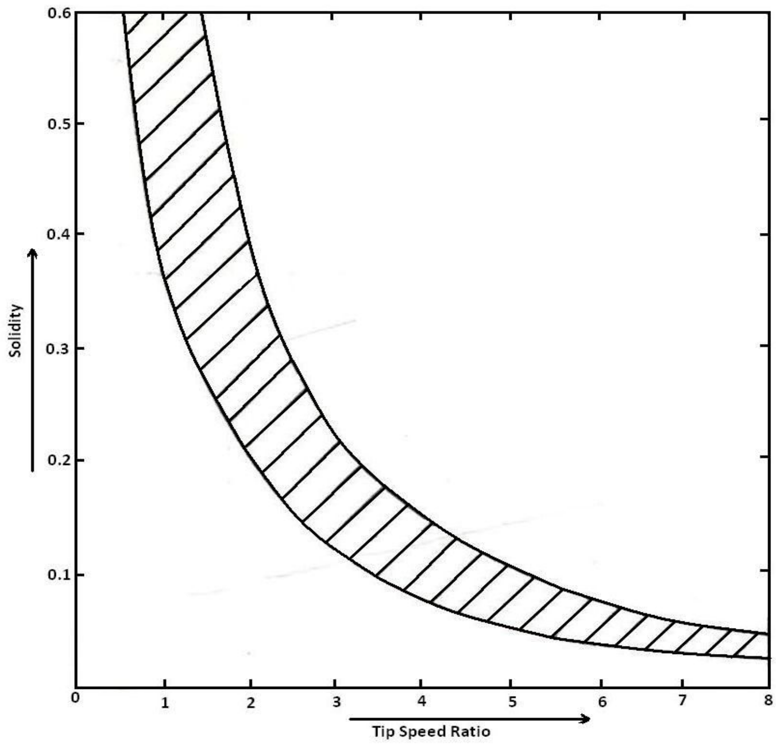


Figure 4.3: Variation of solidity (γ) with tip speed ratio (λ)

4.5 Sample design

We design a three bladed HAWT propeller type wind turbine of 2.5 kW and this turbine is running in Sylhet at a given wind speed of 8.5 km/h at a height of 20 meters, winch is given bellow,

We know,

$$P_e = \frac{1}{2}\rho\, A\, C_p\, U^3 \qquad \cdots\cdots\cdots(i) \qquad ;[From\ equation\ 4.2]$$

$$\gamma = \frac{N\, c\, l}{\pi\, R^2} \qquad \cdots\cdots\cdots(ii) \qquad ;[From\ equation\ 4.8]$$

$$\lambda = \frac{\omega R}{U} \qquad \cdots\cdots\cdots(iii) \qquad ;[From\ equation\ 4.6]$$

Here we have,

$P_e = 2.5\ kW = 2500\ W$

$N = 3$

$\rho = 1.2\ kg/m^3$

$$U = 8.5\ km/h = \frac{8.5 \times 1000}{3600} m/s = 2.36 m/s$$

$A = \pi R^2$

From figure-4.2 we have, $C_p = C_{p,max} = 0.46$

The corresponding, $\lambda = 5.7$

For the corresponding value of tip speed ratio we have the solidity from figure-4.3 is, $\gamma = 0.06$

Now from equation (i) we get,

$$2500 = \frac{1}{2} \times 1.2 \times \pi \times R^2 \times 0.46 \times (2.36)^3$$

$$\Rightarrow R = \sqrt{\frac{2500 \times 2}{1.2 \times \pi \times 0.46 \times (2.36)^3}}$$

$$\Rightarrow R = 14.81\ m$$

The diameter of the rotor is double of the radius of the rotor,

$$D = 2 \times R = 2 \times 14.81 = 29.62\ m = 29.62 \times 3.281 = 97.18\ feet \qquad ;[\because 1m = 3.281 feet]$$

Ma king a small allowance for the size of the hub at the center of the rotor, we assume that the blade length is $l = 13\ m$. Now from the equation (ii) we get,

$$0.06 = \frac{3 \times c \times 13}{\pi \times (14.81)^2}$$

$$\Rightarrow c = \frac{0.06 \times \pi \times (14.81)^2}{3 \times 13} = 1.06\ m$$

From equation (iii) we get the angular velocity of the rotor,

$$5.7 = \frac{\omega \times 14.81}{2.36}$$

$$\Rightarrow \omega = \frac{5.7 \times 2.36}{14.81} = 1.38\frac{rad}{s} = \frac{1.38 \times 60}{2 \times \pi} = 13.23\, rpm$$

We can calculate the total kWHr generate by this machine per year by using equation (2.1),

$$Annual\ energy\ output\ (AEO)\ in\ KWH = 0.01328 \times (rottor\ diameter\ in\ feet)^2 \times \{Average\ wind\ speed\ in\ (mph)\}^3$$

$$= 0.01328 \times (97.18)^2 \times \left(\frac{8.5}{1.609}\right)^3 \qquad ;[\because 1mile = 1.609km]$$

$$= 18491.37\, kWH$$

We assume that the transmission efficiency from the rotor to the generator $N_g = 0.9$ and that the energy conversion efficiency of the generator $N_c = 0.9$ then the electrical power output from the generator is got from equation (4.3),

$$P = P_s \times N_g \times N_c$$

$$\Rightarrow P = 2500 \times 0.9 \times 0.9 = 2025\, W$$

If we select an asynchronous generator for this turbine having a number of poles of 16 and the output frequency is $50\, Hz$ then the synchronous speed for the generator is,

$$N_s = \frac{120f}{p} = \frac{120 \times 50}{16} = 375\, rpm$$

So we need to connect a gearbox for this turbine. Because the angular velocity of the rotor is only $13.23\, rpm$ but for getting the output from the generator we need $375\, rpm$. So the gearbox must have a ratio of 13.23:375 or 1:28.34. The appropriate gearbox is given bellow,

Figure 4.4: Sumitomo Machinery Corp. of America Right Angle, Spiral Bevel Gearbox-Cyclo

Right angle, spiral bevel gearbox with Cyclo® reducer input. Features keyless, steel Taper-Grip® bushing for easy mountingrom Sumitomo Machinery Corp. of America.

- Cycloidal input and oversized bevel gearing provides high overload capability and exceptional reliability for long life
- High performance steel gearing components provide up to 94% efficiency across all ratios

5

Effectiveness of Wind Turbine in Power System

5.1 Introduction

The impact of wind power on the power system depends on the size and inherent flexibility of the power system. It is also related to the penetration level of wind power in the power system.

For voltage management, only areas near wind power plants should be taken into account. Even though there should be enough reactive power reserve in the system during disturbances, the reserve should mainly be managed locally. For intra-hour variations that affect frequency control for load following,

We should look at the area of the synchronously operated system. Direct-current (DC) links connecting synchronously operated areas can also be automized to be used for primary power control. However, their power reserve capacity is usually allocated only as emergency power supply. For the day-ahead hourly production, a relevant area would be the electricity market. The Nordic power market, for instances, includes countries that are situated in different synchronous systems. Large interconnected areas lead to substantial benefits, unless there are bottlenecks in transmission.

If we analyze the incremental effects that a varying wind power production has on the power system, we have to study the power system as a whole. The power system serves all production units and loads. The system has only to balance the net imbalances.

Power system studies require representative wind power data. If the data from too few sites are up scaled the power fluctuations will be up scaled too. If large-scale wind power production with steadier wind resources (e.g. offshore or large wind turbines with high towers) is incorporated into the system, measurements from land or with too low masts will, in turn, overestimate the variations. In addition, most studies will require several years of data.

Figure 5.1 shows the impact that wind energy has on the system. These impacts can be categorized as follows:

- Short-term: by balancing the system at the operational time scale (minutes to hours);
- Long-term: by providing enough power during peak load situations.

These issues will be discussed in more detail in the following sections. For long-term trends affecting the integration of wind power into future power systems, see Section 5.5.

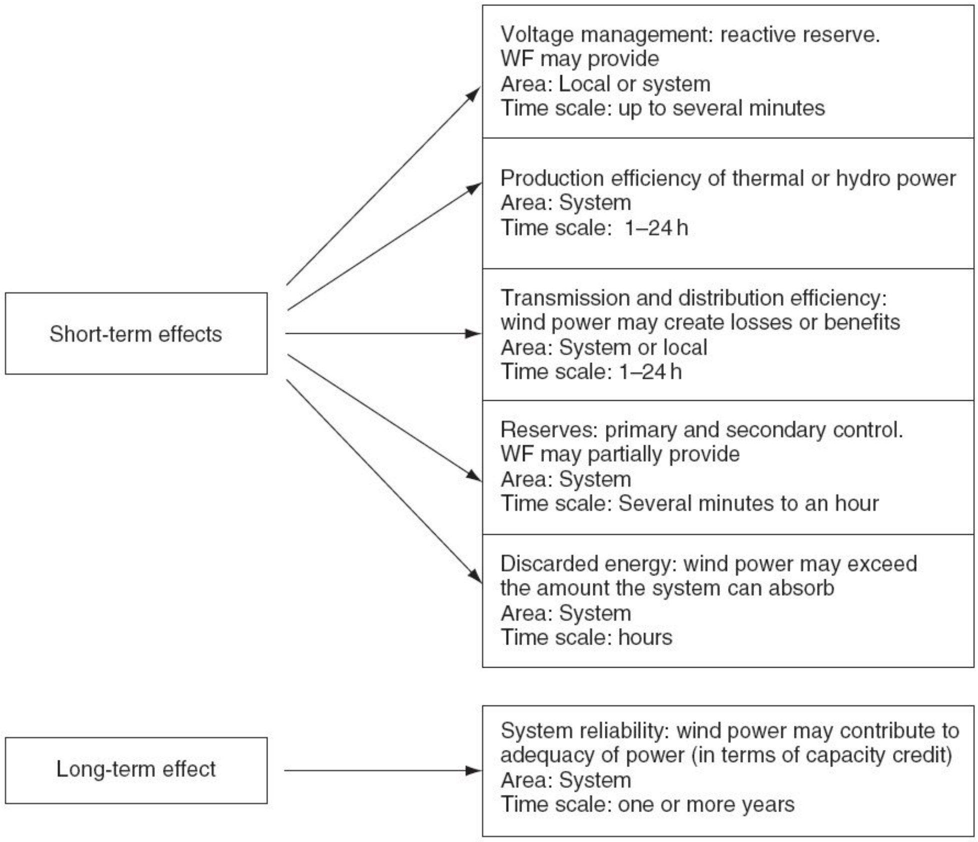


Figure 5.1: Power system impacts of wind power, causing integration costs. Some of the impacts can be beneficial to the system, and wind power can provide value, not only generate cost. Based on H. Holttinen, 2003, Hourly Wind Power Variations and Their Impact on the Nordic Power System (licentiate thesis), Helsinki University of Technology

5.2 Short-term effects on reserves

The additional requirements and costs of balancing the system on the operational time scale (from several minutes to several hours) are primarily due to the fluctuations in power output generated from wind. A part of the fluctuations is predictable for 2 h to 40 h ahead. The variable production pattern of wind power changes the scheduling of the other production plants and the use of the transmission capacity between regions. This will cause losses or benefits to the system as a result of the incorporation of wind power. Part of the fluctuation, however, is not predicted or is wrongly predicted. This corresponds to the amount that reserves have to take care of.

The impact on reserves has to be studied on the basis of a control area. It is not necessary to compensate every change in the output of an individual wind farm by a change in another generating unit. The overall system reliability should remain the same, before and after the incorporation of wind power. The data used for wind power fluctuations are critical to the analysis. It is important not to upscale the fluctuations when wind power production in the system is up scaled. Any wind power production time series that is simulated or based on meteorological data should therefore follow the statistical characteristics that were presented in Section 8.3 (Holttinen, 2003; Milborrow, 2001).

The system needs power reserves for disturbances and for load following. Disturbance reserves are usually dimensioned according to the largest unit outage. As wind power consists of small units, there is no need to increase the amount of disturbance reserve (even large offshore wind farms still tend to be smaller than large condense plants). Hourly and less-than-hourly variations of wind power affect the reserves that are used for frequency control (load following), if the penetration of wind power is large enough to increase the total variations in the system.

Prediction tools for wind power production play an important role in integration. The system operator has to increase the amount of reserves in the system because, in addition to load swings, it has to be prepared to compensate unpredicted variations in production. The accuracy of the wind forecasts can contribute to risk reduction. An accurate forecast allows the system operator to count on wind capacity, thus reducing costs without jeopardizing system reliability.

The requirement of extra reserves is quantified by looking at the variations of wind power production, hourly and intra-hour, together with load variations and prediction errors. The extra reserve requirement of wind power, and the costs associated with it, can be estimated either by system models or by analytical methods using time series of wind power production together with system variables. Wind power production is not straightforward to model in the existing dispatch models, because of the uncertainty of forecast errors involved on several time scales, for instance (Dragoon and Milligan, 2003). Below, we will briefly describe analytical methods with statistical measures.

The effect of the variations can be statistically estimated using standard deviation. What the system sees is net load (load minus wind power production). If load and wind power production are uncorrelated, the net load variation is a simple root mean square (RMS) combination of the load and wind power variation:

$$(\sigma_{total})^2 = (\sigma_{load})^2 + (\sigma_{wind})^2 \qquad \cdots\cdots\cdots (5.1)$$

Where σ_{total}, σ_{load} and σ_{wind} are the standard deviations of the load, net load and wind power production time series, respectively.

The larger the area in question and the larger the inherent load fluctuation in the system the larger the amount of wind power that can be incorporated into the system without increasing variations. The reserve requirement can be expressed as three times the standard deviation (3σ covers 99% of the variations of a Gaussian distribution). The incremental increase from combining load variations with wind variations is 3 times $(\sigma_{total} - \sigma_{load})$. More elaborate methods allocating extra reserve requirements for wind power can be used, especially with nonzero correlations and any number of individual loads and/or resources (Hudson, Kirby and Wan, 2001; Kirby and Hirst, 2000).

On the time scale of seconds and minutes (primary control) the estimates for increased reserve requirements have resulted in a very small impact (Ernst, 1999; Smith et al., 2004). This is because of the smoothing effect of very short variations of wind power production; as they are not correlated, they cancel out each another, when the area is large enough.

For the time scale of 15 min to 1 hour (secondary control) it should be taken into account that load variations are more predictable than wind power variations. For this, data for load and wind predictions are needed. Instead of using time series of load and wind power variations, the time series of prediction errors one hour ahead are used and standard deviations are calculated from these. The estimates for reserve requirements as a result of use of wind power have resulted in an increasing impact if penetration increases. For a 10% penetration level, the extra reserve requirement is in the order of 2–8% of the installed wind power capacity (Holttinen, 2003; Milborrow, 2001; Milligan, 2003).

Both the allocation and the use of reserves cause extra costs. Regulation is a capacity service and does not involve net energy, as the average of regulation time series is zero. In most cases, the increase in reserve requirements at low wind power penetration can be handled by the existing capacity. This means that only the increased use of dedicated reserves, or increased part-load plant requirement, will cause extra costs (energy part). After a threshold, the capacity cost of reserves also has to be calculated. This threshold depends on the design of each power system. Estimates of this threshold suggest for Europe a wind power (energy) penetration of between 5% and 10% (Holttinen, 2003; Milborrow, 2001; Persaud, Fox and Flynn, 2000).

Estimates regarding the increase in secondary load following reserves in the UK and US thermal systems suggest $€\,2-3\,MWh^{-1}$ for a penetration of 10%, and $€\,3-4\,MWh^{-1}$ for higher penetration levels (ILEX, 2003; Dale et al., 2004; Smith et al., 2004). The figures may be exaggerated because the geographical smoothing effect is difficult to incorporate into wind power time series. In California, the incremental regulation cost for existing wind power capacity is estimated to $€\,0.1\,MWh^{-1}$ for a wind energy penetration of about 2% (Kirby et al., 2003).

Also, the recently emerged electricity markets can be used to estimate the costs for hourly production and power regulation. An ideal market will result in the same cost effectiveness as the optimization of the system in order to minimize costs. However, especially at an early stage of implementation of a regulating market, or as a result of market power, the market prices for regulation can differ from the real costs that the producers have.

In a market-based study, Hirst (2002) estimated the increase in regulation (at the second and minute time scale) that would be necessary to maintain system reliability at the same level, before and after the implementation of wind power. The result was that the regulation cost for a large wind farm would be between € $0.04\ MWh^{-1}$ and € $0.2\ MWh^{-1}$. This result applies to systems where the cost of regulation is passed on to the individual generators and is not provided as a general service by the system operator.

In West Denmark, with a wind penetration of about 20 %, the cost for compensating forecast errors in the day-ahead market at the regulating market amounted to almost € $3\ MWh^{-1}$.

In the electricity market, the costs for increased regulation requirements will be passed on to the consumers, and the production capacity providing for extra regulation will benefit from that. Regulation power nearly always costs more than the bulk power available on the market. The reason is that it is used during short intervals only, and that is has to be kept on standby. Therefore, any power continuously produced by that capacity cannot be sold to the electricity spot market. The cost of reserves depends on what kind of production is used for regulation. Hydro power is the cheapest option, and gas turbines are a more expensive option. The cost of extra reserves is important when the system needs an increasing amount of reserves, because of changes in production or consumption, such as increased load. The costs of regulation may rise substantially and suddenly during a phase when the cheapest reserves have already been used and the more expensive new reserves have to be allocated.

The cost estimates for thermal systems include the price for new reserve capacity and assume a price for lower efficiency and part load operation. To integrate wind power fully into the system in an optimal way means using the characteristics and flexibility of all production units in a way that is optimal for the system. Also, a wider range of options in order to increase flexibility can be used. Some examples for existing technologies that could be used to absorb more variable energy sources are:

- Increased transmission between the areas, countries or synchronous systems;
- Demand-side management (DSM) and demand-side-bidding (DSB);
- Storage (e.g. thermal storage with CHP regulating); electrical storage may become cost-effective in the future, but is still expensive today;
- Making the electricity production of CHP units flexible by using alternatives for heat demand (heat pumps, electric heating, electric boilers);
- Short-term flexibility in wind farms. When based on reducing the output of wind power, this means loss of production. The desired flexibility can be achieved more cost-efficiently by conventional generation, if it requires an extensive reduction of wind power output.

Even simple statistical independence makes different variable sources more valuable than simply 'more of the same', such as wind power and solar energy. It may also be beneficial to combine wind power with energy-limited plants where the maximum effect cannot be produced continuously because the availability of energy is limited. This is the case of hydro power and biomass systems. Power systems with large hydro power reservoirs have the option to use hydro power to smooth out the variability of wind power by shifting the time of energy delivery (Krau, Lafrance and Lafond, 2002; Tande and Vogstad, 1999; Vogstad et al., 2000). This is possible also for short response times, within the operating constraints of flow and ramp rates of hydro power (Soder, 1999).

5.3 Other short-term effects

Other effects that wind power has at the operational level of the power system include its impact on losses in power systems (generation and transmission or distribution) and on the amount of fuel used and on emissions [e.g. carbon dioxide (CO_2)]. There is already technology that allows wind farms to benefit power system operation, such as by providing voltage management and reactive reserve (in the case of Type D turbines that are connected to the network or, in a limited way, as in the case of Type C turbines) as well as primary power regulation (Kristoffersson Christiansen and Hedevang, 2002). This issue of reliability is not discussed in detail here.

Wind power can either decrease or increase the transmission and distribution losses, depending on where it is situated in relation to the load. However, large-scale wind power can result in increased transmission between regions. That can lead to increased transmission losses or a larger number of bottlenecks in transmission. For the UK, concentrating the wind power generation in the north would double the estimated extra transmission costs to $€\ 2\ MWh^{-1}$ and $€\ 3\ MWh^{-1}$ at a penetration level of between 20% and 30 %. This would not be the case if production were more geographically dispersed (ILEX, 2003). At more modest penetration levels, transmission costs would decrease.

Large amounts of intermittent wind power production can cause losses in conventional generation. The decreased efficiency of the system is caused by thermal or hydro plants operating below their optimum (startups, shutdowns, part load operation). The optimized unit commitment (i.e. planning the startups and shutdowns of slow-starting units) is complicated by the intermittent output from a wind resource. An accurate prediction of wind power production will help to solve this problem. However, even with accurate predictions, the large variations in wind power output can result in conventional power plants operating in a less efficient way. The effect on existing thermal and/or hydro units can be estimated by simulating the system on an hourly basis. At low penetration levels, the impact of wind power is negligible or small (Grubb, 1991; Soder, 1994), although costs for large prediction errors in a thermal system have been estimated to be about $€\ 1\ MWh^{-1}$ (Smith et al., 2004).

If wind power production exceeds the amount that can be safely absorbed while still maintaining adequate reserves and dynamic control of the system, a part of the wind energy production may have to be curtailed. Energy is discarded only at substantial penetration levels. Whether such a measure is taken depends strongly on the operational strategy of the power system. The maximum production (installed capacity) of wind power is several times larger than the average power produced. This means that there are already some hours with nearly 100% instant (power) penetration (wind power production equals demand during some hours), if about 20% of yearly demand comes from wind power. There is experience from and studies on thermal systems that take in wind power production, but leave, even at high winds, the thermal plants running at partial load in order to provide regulation power. The results show that about 10% (energy) penetration is the starting point where a curtailing of wind power may become necessary. When wind power production is about 20% of yearly consumption, the amount of discarded energy will become substantial and about 10% of the total wind power produced will be lost (GarradHassan, 2003; Giebel, 2001). For a small thermal island system (e.g. on Crete, Greece) discarded energy can reach significant levels already at a penetration of 10% (Papazoglou, 2002).
For other areas, integration problems may arise during windy periods, if production in the area exceeds demand and also the transmission capacity to neighboring systems. This can be especially pronounced during windy, cold periods when there is also a substantial share of local, prioritized CHP production, as

is the case of Denmark. When initially in West Denmark wind energy was discarded, this happened at penetration levels of 20% rather than 10 %. With energy system models it has been estimated that by using the existing heat storage and boilers of CHP production units together with wind power, and assuming some flexible demand and electrical heating, a 50% wind power penetration could be possible without discarding any energy (Lund and Munster, 2003).

Wind power is renewable energy, practically free from CO_2 emissions. CO_2 emissions from the manufacturing and construction are in the order of $10g\ CO_2\ kWh^{-1}$. If wind energy replaces generation that emits CO_2, CO_2 emissions from electricity production are reduced. The amount of CO_2 that will be abated depends on what production type and fuel is replaced at each hour of wind power generation. This will be the production form in use at each hour that has the highest marginal costs. Usually, this is the older coal-fired plants, resulting in an CO_2 abatement of about $800 - 900g\ CO_2\ kWh^{-1}$, often cited as the CO_2 abatement of wind energy. This is also true for larger amounts of wind power production, for countries that generate their electricity mainly from coal. In other countries, though, there may be a different effect if large amounts of wind power are added to the system. There may not be a sufficient number of old coal plants whose capacity can be replaced by wind power production throughout the year. During some hours of the year, wind power generation would replace other production forms, such as the production of gas-fired plants (CO_2 emissions of gas are $400 - 600g\ CO_2\ kWh^{-1}$), or even CO_2-free production (e.g. hydro, biomass or nuclear power). Instant (regulated) hydro production can be postponed and will replace condensing power at a later instant. Simulations of the Nordic system, for example, which is a mixed system of thermal and hydro production, result in a CO_2 reduction of $700g\ CO_2\ kWh^{-1}$ (Holttinen and Tuhkanen, 2004). This is the combined effect of wind power replacing other fuels.

5.4 Long-term effects on the adequacy of power capacity

The intermittent nature of wind energy poses challenges to utilities and system operators. These must be able to serve loads with a sufficiently low probability of failure. The economic, social and political costs of failing to provide adequate capacity to meet demand are so high that utilities have traditionally been reluctant to rely on intermittent resources for capacity.

Dimensioning the system for system adequacy usually involves estimations of the LOLP index. The risk at system level is the probability (LOLP) times the consequences of the event. For an electricity system, the consequences of a blackout are large, thus the risk is considered substantial even if the probability of the incident is small. The required reliability of the system is usually in the order of one larger blackout in 10–50 years.

What impact does wind power have on the adequacy of power production in the system – can wind power replace part of the (conventional) capacity in the system? To answer this question, it is critical we know wind power production during peak load situations. This also means that to assess the ability of wind power to replace conventional capacity (i.e. the capacity credits) it is important either to have representative data for several years (one year is not enough) or to make a variability assessment (Giebel, 2001; Milligan, 2000)

Some variable sources can be relied on to produce power at times of peak demand. Solar energy, for instance, follows air-conditioning loads, and wind energy reflects heating demand. If a diurnal pattern in wind power production coincides with the load (e.g. wind power production increases in the morning and decreases in the evening) this effect is beneficial. However, in most cases there is no correlation between load and the availability of this variable source. In Northern Europe, for example, even if the seasonal variations mean that more wind power is available in winter than in summer, there is not a strong correlation between the high loads in winter and high wind power production. In Denmark, the correlation is slightly positive (about 0.2), but there is usually less correlation during higher-load winter months than in the summer months.

In Northern Europe, the load is strongly correlated to outside temperature. The correlation between wind power production and temperature has an effect on the adequacy of power production, when determining the capacity value of wind power (see Figure 5.2). Looking at wind power production during the 10 highest peak load hours each year, one can see it ranges between 7–60% of capacity (1999–2001 in the Nordic countries; Holttinen, 2003).

Nevertheless, variable sources can save thermal capacity. Since no generating plant is completely reliable, there is always a finite risk of not having enough capacity available. Variable sources may be available at the critical moment when demand is high and many other units fail. Fuel source diversity can also reduce risk.

It has been shown in several studies that if the capacity of a variable source is small (low system penetration) the capacity value equals that of a completely reliable plant generating the same average power at times when the system could be at risk. As the penetration increases, variable sources become progressively less valuable for saving thermal capacity (ILEX, 2003). The dispersion of wind power and a positive correlation between wind power and demand increase the value of wind power to the system. For very high penetration levels, the capacity credit tends towards a constant value there is no increase in the capacity credit when increasing wind power capacity. This will be determined by the LOLP without wind energy and the probability of zero wind power (Giebel, 2001).

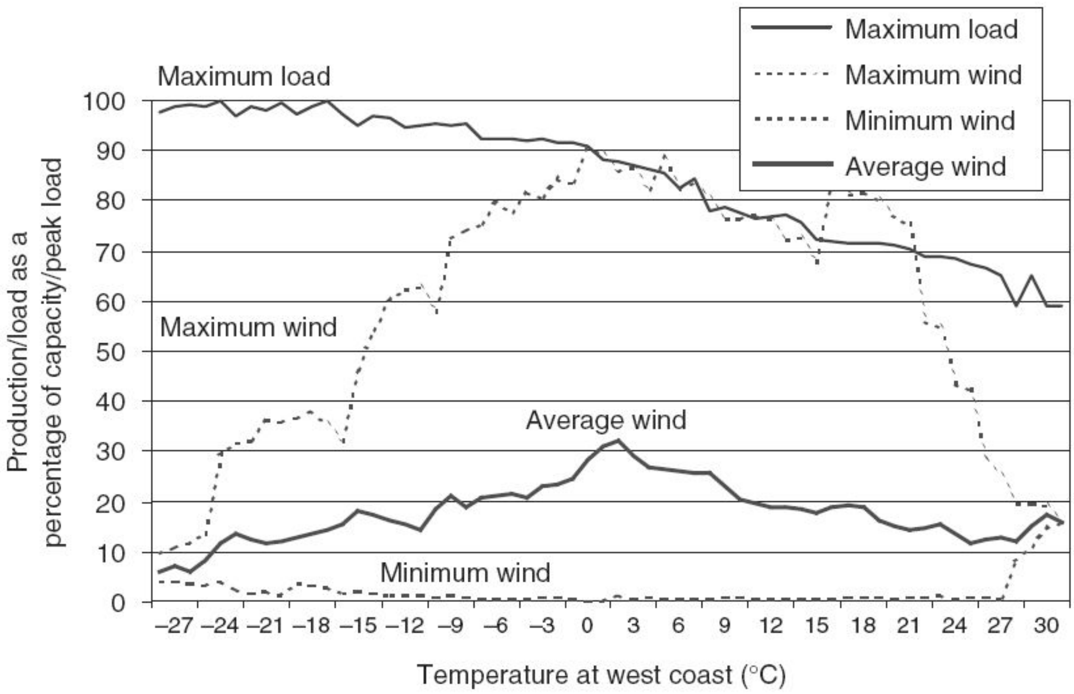


Figure 5.2: Correlation of temperature with wind power production and load in a cold climate (Finland), with geographically dispersed wind power. Note: there were 48 h (0.1% of time) below $-23° C$ and 549 h (1.6% of time) below $-14° C$ during the years 1999–2002. Reproduced, by permission, from H.

Holttinen, 2003, Hourly Wind Power Variations and Their Impact on the Nordic Power System (licentiate thesis), Helsinki University of Technology

If there is a substantial amount of wind power in the system (greater than 5% of peak load) an optimal system to accommodate wind power would contain more peaking and less base plants than a system without wind power. For hydro-dominated systems, where the system is energy restricted instead of capacity restricted, wind power can have a significant energy delivery value. As wind energy correlates only weakly with hydro power production, wind energy added to the system can have a considerably higher energy delivery value than the addition of more hydro power (Soder, 1999).

5.5 Wind power in future power systems

Large-scale wind power still lies in the future for many countries. There are long-term trends that can influence the impact of wind power on the system. If there are large amounts of intermittent energy sources in the system, new capacity with lower investment costs (and higher fuel costs) will be favored. The trend of increasing distributed generation from flexible gas turbines is beneficial for the integration of wind power, as is increasing load management. A greater system interconnection is highly beneficial as well: wind power spread all over Europe would be quite a reliable source. The use of electric vehicles will open new possibilities for variable and intermittent power production. Producing fuel for vehicles that are used only about 1000 hours per year will ease the flexibility needs in power systems.

The expected developments of wind power technology will affect the impact that wind power has on power systems. Very large wind farms (hundreds of megawatts) are one trend that can pose serious challenges to the integration of wind power, as they concentrate the capacity. As a result, the smoothing effect of variations by geographical spreading is lost. However, such large wind farms will also pave the way for other technologies that will help with integration. Increasingly sophisticated power electronics and computerized controls in wind farms, as well as an improved accuracy in wind forecasts, will lead to improvements in the predictability and controllability of wind power. Large wind energy power plants will mean that there are new requirements regarding the integration of wind power into the power system. Increasingly, wind farms will be required to remain connected to the system when there are faults in the system. They will be expected to withstand nearby faults without experiencing problems in power production during and after the faults. And they will be expected to provide reactive power support to the system during the fault.

5.6 Effectiveness of using wind turbine in power generation for Bangladesh

The countries like Bangladesh whose has not enough sources of fuels, those countries must need the wind power. Bangladesh also a poor country and its people are living under the poverty. So Bangladesh must need to reduce the price of the per unit electricity for its people. For this Bangladesh need to use renewable energy source like wind. By using wind power Bangladesh government can reduce the price of the electricity. And also Bangladesh Government can supply electricity to its people equally and spontaneously.

6

Wind Power Economics

6.1 The Economic Case for Domestic Wind Turbines

This article explores the economic feasibility of domestic wind power. This was intrigued by the national debate over the viability of domestic wind power and decided to perform a worked costing to compare it with electricity purchased from the national grid. The results are surprising - domestic wind power can be as cheap as conventional non-renewable energy, even before any additional environmental benefits are considered.

6.2 Why domestic wind power?

We should be sourcing energy locally. By generating power at or near our homes and offices, we can:

1. Reduce our dependency on the national grid
2. Distribute the load on the system
3. Cut down on the energy lost in transmission
4. Minimize unsightly power cables and pylons

For distributed power generation to become a reality, it needs to be economically viable when compared to traditional power sources.

6.3 Comparing electricity prices

The cost of electricity is typically measured in taka per kilowatt hour, abbreviated as Tk/kWh. For domestic wind energy to compete on purely economic grounds we must compare the cost of domestic versus grid electricity.

6.4 The Calculation

This calculation will make some assumptions about the type of wind generator an individual might install at home. The cost of the turbine and installation will be priced using manufacturer's Recommended Retail Price data. Dividing the total system cost by the total number of kilowatt hours of electricity generated will yield a cost per kilowatt hour. We can then compare this figure with electricity purchased from the grid to see which is cheaper.

6.5 Starting Assumptions

We'll make these assumptions:

- The occupants of a large house (approximately 4 adults) require 4 megawatt hours of electricity each year to meet their energy needs, which can be met by
- A Proven 2500W wind turbine[1] installed on a self-supporting tilt-up mast exposing it to smooth (laminar) airflow, which is
- Located in an average wind area in the Bangladesh, with a
- System lifetime of 20 years (after which time it will be replaced).
- The system is installed as part of a new-build, and therefore attracts 0% VAT [2]

[1] The Proven WT2500 wind turbine is made by a Scottish company. It belongs to the 'heavy metal' school of wind turbines because it is solidly built, and while initially more expensive than its American or European equivalents, will have lower lifetime costs. It's also very tough and able to withstand extreme weather conditions; an important consideration as worsening climate change brings more severe and variable weather.

[2] If the government were serious about combating climate change, they would remove VAT from all green products, regardless of whether they were installed as part of a new home, or retrofitted to an existing home.

6.6 Lifetime electricity production

The average wind speed in the Thakurgaon, Bangladesh is approximately 6.59m/s.

In this wind speed it will produce on average:

- 4700 kWHr per year, or
- 391.7 kWHr per month, or
- 13.1 kWHr per day

Over 20 years this turbine will produce $= 20 \times 1700 = 94000\ kWHr$.

6.7 System components and total cost

The following costs are taken from the Proven's price list and include the turbine, charge controller system and masts.

Table 6.1: Price list of domestic connected wind turbine

Components	Price
2.5kW wind turbine 24V output	100000/-
2.5kW, 24V DC battery charging controller. Includes 2 DC and 3 AC divert load connections, V&I meters plus 8 system status indicators.	60000/-
Tilt-up self supporting wind turbine mast (6.5m)	35000/-
Tirfor winch with 20 meters wire rope + strop	10000/-
Lead-acid battery bank, approx 700AHr capacity	20000/-
Total cost	225000/-

6.8 Cost of wind turbine electricity

Over twenty years this system will produce 94000 kWHr of electricity at a cost of Tk-225000/-.

The cost per kilowatt hour is therefore= $\frac{225000}{94000}\ Tk/kWHr = 2.39\ Tk/kWHr$.

6.9 Cost of grid electricity

Our domestic electricity bill in May 2009 charged the following:

Table 6.2: Price list of grid connected electricity.

Components	Price
Electricity consumption over 30 days	238 kWHr
Charge rate	2.88 Tk/kWHr
Cost	Tk 685/-
Fixed service charge	Tk 5/-
Demand charge	Tk 30/-
Total cost of electricity	Tk 720/-
Total cost of electricity including VAT at 5%	Tk 756/-
Actual unit cost of electricity= $\frac{Tk\ 756}{238\ kWHr}$	3.18 Tk/kWHr

6.10 Comparison of grid versus domestic wind turbine

This comparison is extraordinary. A good quality well-specified domestic wind turbine produces cheaper electricity (0.042 Tk/kWHr) over its 20 year lifetime than grid-purchased energy (3.18 Tk/kWHr)! Already, at today's artificially low energy prices, home wind power is more viable than grid energy, even without considering all the other benefits such as:

- Reduced green house gas emissions (to near zero)
- Self-reliance and immunity from failure of the national grid
- No unsightly power lines scarring the country
- Protection against inevitable future energy price rises as oil production peaks then declines

6.11 Conclusion

The case is compelling - domestic wind turbines in the Bangladesh can produce, at an individual household level, cheaper electricity than coal, oil, gas and nuclear power stations. They reduce our greenhouse gas emissions and cost less.

7

Wind Power in Bangladesh

7.1 Introduction for prospects and utilization initiatives

Wind can be a vital source of energy if properly utilized and exploited. But before high-end projects are implemented, adequate research should be done to study the feasibility and determine a suitable type of project to implement. The primary parameter needed is wind speed and direction. Over the past years, many organizations have made many attempts to collect data on wind resources in Bangladesh. Based on this collected data, many small wind energy projects have been undertaken.

7.2 Scenario of resources

Bangladesh is situated between 20.30 - 26.38 degrees North latitude and 88.04 - 92.44 degrees East. It has seven hundred Km coastal line, analysis of upper air data by CWET India show that wind energy resource of Bangladesh is not good enough for grid connected wind parks. At present, several wind resource assessment program (WERM, SWERA, WRAP of BPDB) is ongoing in the country. From the previous studies it can be inferred that the small wind turbines can be installed in the coastal regions of the country.

7.2.1 Wind Data from Bangladesh Meteorological Department

Most of the previous wind speed data in Bangladesh available from the Bangladesh Meteorological Department. Meteorological stations measure winds at lower height. However, normal hub-heights of modern wind turbines ranges from 20 to 40m.Thus using meteorological data, designing wind energy conversion system would end in a failure and there are some previous experiences.

7.2.2 Wind data analysis by BUET at Gajipur

Wind data were recorded from august 1997 to July 1999 as a daily basis and recorded by a data logger. The wind speed frequency distribution is processed from these data and fitted to Weibull function to determine the nature of wind regime. The table shows data for 1 year with the shape factor k and scale factor c of the Weilbull parameters.

Table 7.1: Standard deviation method derived from one-year data at Chandona (Aug.'98 -Jul.'99)

Month	k	$c\ (m/s)$	$V_{mean}\ (m/s)$
January	2.95	3.06	2.41
February	2.80	3.31	2.95
March	2.45	3.69	3.27
April	2.56	4.85	4.31
May	2.53	4.76	4.23
June	2.90	5.28	4.20
July	3.20	3.77	3.20
August	2.21	3.74	3.31
September	2.08	3.12	2.76
October	2.18	2.54	2.21
November	2.31	2.63	2.33
Decmber	3.00	2.56	2.29

7.2.3 Wind Energy Study Project (WEST)

Table 7.2: Monthly average wind speeds from seven WEST stations at 25 meters height in 1996-1997.

Name of the wind speed monitoring station						
Month	**Patenga**	**Cox's Bazar**	**Teknaf**	**Char Fassion**	**Kuakata**	**Kutubdia**
September	3.36	3.69	3.46	3.34	3.77	3.58
October	3.2	3.74	3.30	3.70	2.18	3.98
November	2.61	2.93	2.29	3.75	1.98	3.23
Decmber	2.97	1.78	1.44	3.9	3.35	3.38
January	3.25	2.33	1.99	2.8	3.18	3.67
February	2.66	1.99	1.90	2.69	3.37	3.29
March	3.13	2.42	2.26	3.54	4.84	3.53
April	2.88	1.84	1.65	3.29	4.93	3.11
May	4.96	3.97	3.09	4.81	6.28	4.89
June	5.83	4.64	3.26	5.76	7.31	5.90
July	5.67	4.8	4.33	5.22	7.34	6.17
August	5.13	4.31	4.03	5.17	7.33	5.34

7.2.4 Wind data study at Saint Martin's Island

Recently a project on "Feasibility Study on R&D of Renewable Energy (Solar, Wind, and Micro-Mini Hydro)" has been undertaken by the Institute of Fuel Industrial Research (BCSIR). Under this program, wind speed data have been collected in the Saint Martin's Island. Research Development (IFRD), of Bangladesh Council of Scientific.

Table 7.3: Monthly average wind speeds in the Saint Martin's island [IFRD, 2002]

Month	$V_{avg}\ (m/s)$	$V_{max}\ (m/s)$
January	5.08	23.32
February	4.71	19.78
March	4.29	18.94
April	3.58	20.03
May	5.75	26.30
June	5.96	29.80
July	5.33	24.20
August	5.96	20.40
September	4.79	17.70
October	4.17	15.90
November	3.79	14.50
Decmber	4.08	15.20

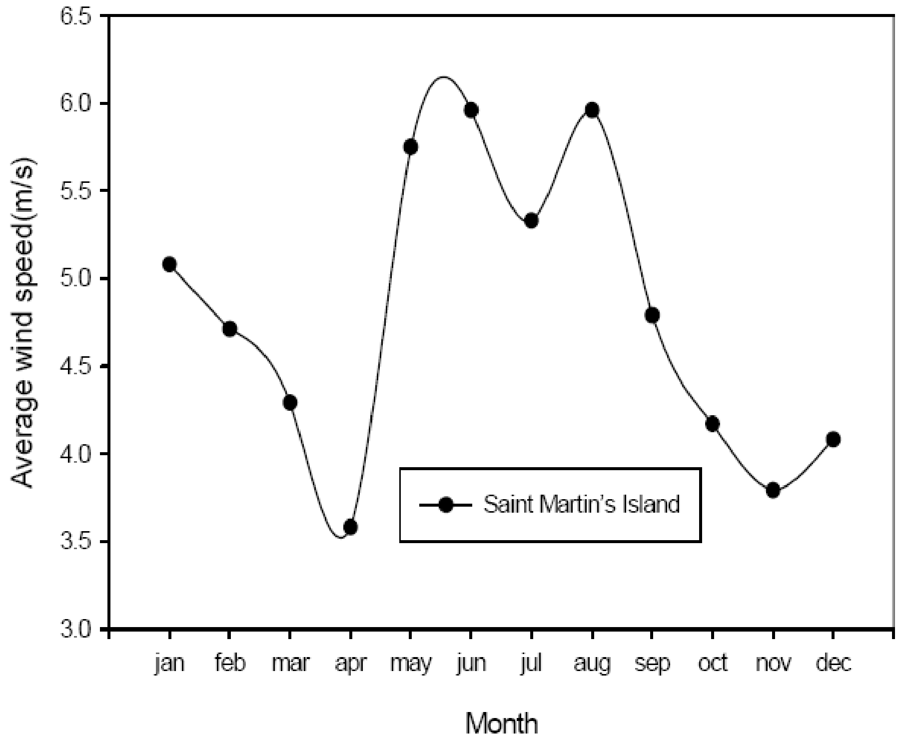


Figure 7.1: Monthly average wind speed at Saint Martin's Island.

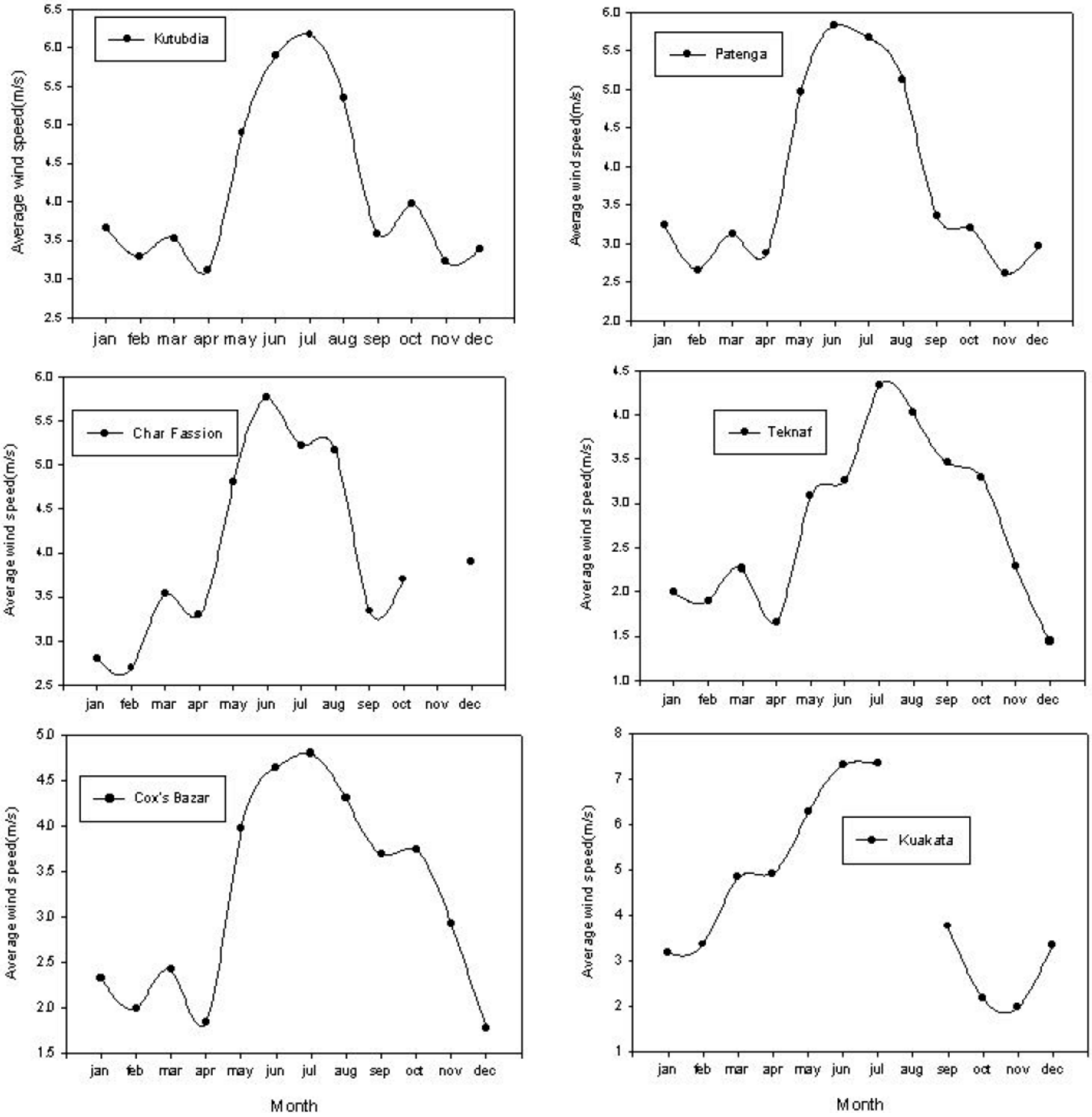


Figure 7.2: Monthly average wind speed at different locations.

7.3 Utilization initiatives

From the previous studies it can be inferred that the small wind turbines can be installed in the Coastal regions of the country. However, scope of utilization of wind energy resources can become effective in certain cases of exclusive applications including wind water pumping and power generation through Wind-Diesel-hybrid systems conducted by BPDB; Muhuri Dam area at Feni has bright prospects of electricity generation from wind. In the above-mentioned backdrop BPDB has decided to undertake the Wind Resource Assessment Program (WRAP) at the Muhuri Dam site for one year.

7.3.1 Wind Energy Program under Grameen Shakti

Grameen Shakti (GS) installed 4 hybrid power stations (combination of wind turbine and diesel generator) in four cyclone shelters of Grameen Bank of which 3 are 1.5 kW and one is 10 kW.

7.3.2 Wind Resource Assessment Program (WRAP) of BPDB

According to preliminary study diesel generator) in four cyclone shelters of Grameen Bank, of which 3 are 1.5 kW and one is 10 kW.

7.3.3 Wind Energy Program under Bangladesh Center for Advanced Studies (BCAS)

- Energy Resource: Wind Turbine
- Type of installation: Water pumping wind mill irrigation
- Capacity of installation: 1X1.0 KW, 3X1.5 KW, 1X10 KW
- Location of Installation: Patenga (Coastal Area), Chittagong
- Functional Status: Functioning

7.3.4 Wind Energy Program under Bangladesh Rural Advancement Committee (BRAC)

Program 1-

- Energy Resource: Wind Turbine
- No of installation: 3
- Capacity of installation: 0.9 KW
- Location of Installation: Coastal Area of Bangladesh
- Functional Status: Functioning

Program 2-

- Energy Resource: Wind-Diesel Hybrid System
- No of installation: 7
- Capacity of installation: 4.32 KW
- Location of Installation: Coastal Area of Bangladesh
- Functional Status: Functioning

7.4 Conclusion for prospects and utilization initiatives

Though some of the wind turbine is installed for pumping purpose, it is not enough compared to our total available wind energy resource in Bangladesh. From Table 6.2 and Figure 6.1, Figure 6.2 it can be seen that from May to August wind speed are higher, wind generated electricity and wind pumps can provide irrigation facilities in that time. All data in table 6.2 is taken in coastal region so we may use this wind for producing electricity in those remote areas for running ice mills and to preserve fishes. From seven WEST station it was found that the average annual wind speed values at 25 meter height for the seven stations vary from 2.96 m/sec to 4.54 m/sec. The highest average annual value (4.54 m/sec) was observed in Kuakata and the lowest value (2.96 m/sec) was observed in Teknaf. From table 7.3 we find the wind speed is good enough to produce electricity in Saint Martin’s Island. Though wind speed value is less than 7 m/s afterwards we know average hub height is 20 to 40m and that will increase the wind speed and feasible to electricity generation. It is observed that wind speeds of Chandona are low .The wind speed is very high during monsoon period (June-July) and very lean from October to February. From the analysis of wind resource assessment it is found that 300-600 watt capacities Wind Electric Generators (WEGs) are preferable and windmill for water pumping are prospective for that site.

During the driest season, there is a very strong flow of North-West direction wind and this is the season for paddy cultivation in Bangladesh, so during this period wind pump provide irrigation facilities. Wind pumping can play a significant role in the supply of water for irrigation and drinking for the rural areas in Bangladesh. In most of the areas in Bangladesh, the pumping head is less than 6m, which is appropriate for using diaphragm pump and man powered pump, by these pump available wind power can be produced good result with a suitable rotor.

7.5 Introduction for wind power for rural areas of Bangladesh

Recent developments in the area of wind power generation are very encouraging; particularly in the tropical regions of Asia and Australia. From irrigation projects in India to power supply in the remote farms in Australia, wind power generation can play a vital role.

With the increasing demand of electricity, Indian Government has prepared a master plan to promote the non-conventional energy sources. A target is set to generate 10% power from renewable energy sources by the year 2012, which is only 1% today. Wind energy is at the top of the plan. So far, wind power projects of 1345 MW are commissioned and feeding the power to the utility grid in the country. A rapid growth of wind power sector is seen in the country. The estimated technical potential of wind power is around 45000 MW. India ranks amongst the top five wind power production countries in the world. Various state governments in the country have also declared the promotional policies to encourage the wind power sector.

The water pumping windmill, reciprocating type being of low efficiency has an economic performance inferior to that of an electric motor pump and even to that of a diesel engine pump. It is suggested that the technical performance of the wind water pump can be significantly improved if a centrifugal pump is used in place of the reciprocating type.

7.6 Wind data analysis

Bangladesh farming needs adequate supply of irrigation water at right time and in right quantities for maximum agricultural production. About 50 % of irrigation pump operate at a head of 6 m or less, depending on the terrain of the country. For driving these pumps, either diesel engine or electric motors are used. These pumps can be driven with the help of wind turbine.

Bangladesh is situated between $20°34'$ to $26°38'$N latitudes and $88°01'$ to $92°41'$ E longitudes with nearly 130 million people living on 1,44,000 sq. km. of area. It has 724 km long coastal belt, around 200 km hilly-coast-line and about 50 islands in the Bay of Bengal. The strong south/south-westerly monsoon wind, coming from the Indian Ocean, after traveling a long distance over the water surface, enter into the coastal areas of Bangladesh. This trade wind blows over the country from March to October. This wind speed is enhanced when it enters the V-shaped coastal regions of our country.

In this study, an attempt has been made to investigate the application of wind energy for water pumping in coastal and rural areas of Bangladesh. For this purpose, 16 years wind speed data of 20 meteorological stations have been studied and the wind velocity is estimated at 20 meters height by using power law expression (Table 6.4). The meteorological department of Bangladesh collects 3-hourly wind speed data with the help of vertical axis cup type anemometers. These wind data for the period 1981-1996 of 20 stations were taken and monthly average speeds were computed for all the 20 stations.
Wind velocity changes with height. The rate of increase of velocity with height depends upon the roughness of the terrain. The variation of average wind speed can be determined from the following power law expression,

$$\frac{V_z}{V_{ref}} = \left(\frac{h}{h_{ref}}\right)^{\alpha} \qquad \cdots\cdots\cdots (7.1)$$

where, V_z and V_{ref} are the average speeds at height h in meter and at the reference height of $h_{ref} = 10m$ above the ground respectively and α varies from 0.1 to 0.4 depending on the nature of the terrain.

Table 7.4: Average Wind Speed (m/s) at 20 Meters Height at Different Locations in Bangladesh

Locations	Months												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Mean
Barisal	2.90	2.57	2.57	3.56	3.23	2.90	2.71	2.64	2.57	2.11	2.07	2.05	2.66
Bogra	1.95	2.20	3.05	4.03	4.15	3.66	3.42	3.05	2.56	2.20	1.83	1.71	2.82
Chittagong	3.64	2.88	4.95	5.01	5.51	6.89	7.09	6.83	4.64	2.82	3.39	2.20	4.65
Comilla	2.26	2.70	2.57	5.45	3.83	3.20	2.88	2.95	1.82	2.38	1.63	1.70	2.78
Cox'sBazar	3.76	3.83	4.51	5.58	3.83	4.14	3.83	3.95	3.20	3.26	2.57	3.26	3.81
Dhaka	3.39	3.26	4.39	5.77	6.33	5.71	6.01	5.89	4.39	3.45	2.64	2.95	4.52
Dinajpur	2.68	2.44	4.88	2.44	2.93	2.68	2.56	2.44	2.44	3.54	2.44	2.44	2.83
Hatiya	3.04	2.64	4.16	3.97	4.82	6.47	5.75	2.64	2.96	2.77	3.06	2.57	3.74
Jessore	2.88	2.95	4.95	8.34	8.34	6.27	6.15	4.95	4.33	3.45	3.32	3.20	4.93
Khepupara	4.20	4.39	3.83	7.09	5.83	4.71	4.14	3.95	3.57	3.70	2.95	2.57	4.24
Khulna	2.96	1.65	3.04	3.05	4.16	3.89	3.31	2.44	2.51	1.98	3.31	2.38	2.89
Kutubdia	1.77	1.82	2.32	2.70	2.77	3.65	3.61	3.14	2.11	1.45	1.19	1.29	2.32
Mongla	1.07	1.25	1.72	2.51	2.92	2.63	2.48	2.35	1.83	1.27	1.02	1.01	2.20
Rangamati	1.45	1.65	4.42	3.10	2.11	3.23	1.72	2.24	1.45	1.45	1.39	1.59	2.15
Sandip	2.32	3.01	3.20	4.83	2.44	3.83	3.39	2.70	2.32	1.63	1.70	1.70	2.76
Sylhet	2.20	2.93	3.29	3.17	2.44	2.68	2.44	2.07	1.71	1.95	1.89	1.83	2.38
Teknaf	3.70	4.01	4.39	4.01	3.32	3.89	3.83	2.88	2.44	2.20	1.57	1.76	3.17
Patenga	6.22	6.34	7.37	7.92	8.47	8.69	9.20	8.54	7.48	6.93	6.71	5.91	7.48
Sathkhira	4.21	4.40	3.84	7.10	6.11	4.76	4.27	4.03	3.62	3.78	3.54	2.81	4.37
Thakurgaon	4.15	5.06	7.93	8.43	8.66	8.05	7.93	6.59	6.34	5.98	5.25	4.76	6.59

Attempt would be made to give a detailed idea about various kinds of presentation of the wind data at different sites at 20 m height. This would provide information to make decision whether that site has reasonably potential for the operation of wind machine. Table 6.5 shows the monthly variation of average wind speed for several places in Bangladesh. It can be seen that wind speeds are higher from March to August for all places. A wind turbine, if properly designed and located, can supply enough wind energy. The peak rainfall in Bangladesh occurs during the months of June, July and August. But peak wind speeds are available during the hottest and driest months of March, April and May. During this period wind turbine may be used for water pumping for irrigation, if the water is previously stored in a reservoir during the monsoon season. From September to February the velocities are not at all promising for harnessing power. It may be noted that there is wide variation of wind velocity in the coastal areas throughout the year. Patenga, Chittagong, Thakurgaon, Jessore, Khepupara etc. are relatively prospective site for extraction of wind energy.

The wind power per unit area of approach is proportional to the cube of wind speed and can be expressed as P/A = 0.6V3(watts), where P/A is in W/m2 and V is in m/s. The available wind power represents the strength of wind and theoretically 59% of this power is extractable but practically only 30-40% can be extracted.

Practically, extractable power by any type of windmill can be written as, Pe=0.1AV3 (watt), where A is the total swept area of the rotor blades and V is wind speed (m/s).

Extracted power per square meter of swept area for different months for 20 locations in Bangladesh is shown in Table 7.5. From this table, it can be seen that wind energy can be used in the hottest months i.e., March, April and May for irrigation purposes.

Table 7.5: Theoretical Available Power of Different Locations at 20 Meters Height in Bangladesh

Locations	Potential Months For Extracting Wind Power	Average Wind Velocity (m/s)	Theoretical Available Power (W/m^2)
Barisal	April to May	2.66	11.27
Bogra	April to June	2.82	13.40
Chittagong	March to September	4.65	60.49
Comilla	March to September	2.78	12.90
Cox'sBazar	May to August	3.81	33.17
Dhaka	March to October	4.52	55.26
Dinajpur	March to August	2.83	13.55
Hatiya	March to July	3.74	31.29
Jessore	April to September	4.93	71.84
Khepupara	February to September	4.24	45.88
Khulna	April to July	2.89	14.47
Kutubdia	April to August	2.32	7.49
Mongla	May to August	2.20	6.39
Rangamati	April to May	2.15	5.97
Sandip	April to July	2.76	12.55
Sylhet	April to July	2.38	8.13
Teknaf	February to September	3.17	19.06
Patenga	February to November	7.48	251.11
Sathkhira	March to September	4.37	50.16
Thakurgaon	March to August	6.59	172.04

7.7 The wind energy can used in prospective resources of Bangladesh

7.7.1 Shrimp cultivation

There is more than 0.2 million hectres of shrimp cultivated land in the coastal regions of Bangladesh. But due to shortage of electricity it is not possible to apply the modern methods of shrimp cultivation. Shrimp cultivation season in Bangladesh begins from March and ends by September. By applying the semi-intensive methods of shrimp and other fish cultivation, which requires electricity, production can be increased by 25-30 times. Electricity is essential for semi-intensive and intensive methods of shrimp cultivation. But it is difficult and expensive to take the national grid or transport fossil fuels to those remote areas and the off shore islands. On the other hand there prevails strong trade winds in those regions from which electricity generation and supply it through localized grid is possible. This electric power will be cheaper and pollution free.

7.7.2 Fish Preservation

About 15 million people live in the coastal regions and the off shore islands of our country. More than 80% of these people live on fishing. The fishing season in the Bay of Bengal is from July to October. During this season, tends of thousands of fishes are netted in the Bay. Due to scarcity of ice, a large portion of these netted fishes are rotten and are thrown into the sea. Running the ice mills by wind generated electricity in those remote areas; this problem can be solved to some extent.

7.7.3 Boro Paddy Cultivation

Boro Paddy cultivation in Bangladesh is from March to May. During this driest season, there prevails a very strong flow of the North-Westerly Trade Wind in the country, specially, in the northern districts. High yielding varieties of paddy are cultivated in this season.

So, irrigation is the must. Wind generated electricity and the wind pumps can help irrigation.

7.7.4 Social Benefits

The application of wind energy may result in significant improvement of the quality of life in the remote rural areas and off shore islands. This development may prevent the tendency of the people to migrate to the cities. Wind energy can help growing small industries in the remote areas and thus can create many jobs and self-employment opportunities. Wind energy can convert millions of idle night hours into effective working hours in the rural area where people stop working before sunset and start working after 6 or 7 a.m.

7.7.5 Sizing the Wind Pump for Patenga, Bangladesh

An empirical equation developed for wind pump rotor sizing for Patenga, Bangladesh is given below:

$$HQ = C \times D^2 \times V^3 \qquad \cdots\cdots\cdots (7.2)$$

Where,

C = Constant (here, 8.47)
HQ = Volume-Head product (m^4/day)
Q = Water requirement per day ($m^3/\,day$)
H = Water tank height (m)

D = Diameter of the rotor (m)
V = Average wind velocity (m/s)

Sizing of the wind pump for Patenga, Bangladesh can be calculated using equation 7.2, or more easily from the nomogram given in Figure-7.3 by following steps.

Step-1: Locate the volume-head product along the Y-axis on the graph on the left side.
Step-2: Move horizontally right to intercept the line for the average wind velocity 5.91 m/s.
Step-3: Move downward to intercept the X-axis referring to the rotor diameter.

Another way of sizing of the wind pump for Patenga, Bangladesh could be carried out using equation 7.2 or more easily from the nomogram given in Figure 7.4, if the average wind velocity (m/s) is known.

Step-1: Locate the average wind velocity along the X-axis on the graph on the right side. In the case of the example, average wind velocity is taken as 5.91 m/s.
Step-2: Move upwards to intercept the line for $D = 1\,m^2$
Step-3: Move horizontally left to intercept the Y-axis referring to the volume-head product. This results in $Q = 1748.42\ m^2/day$. The diameter of the pump could be established from the supplier's catalogues, depending on the stroke adjustment scale and standard pump diameters.

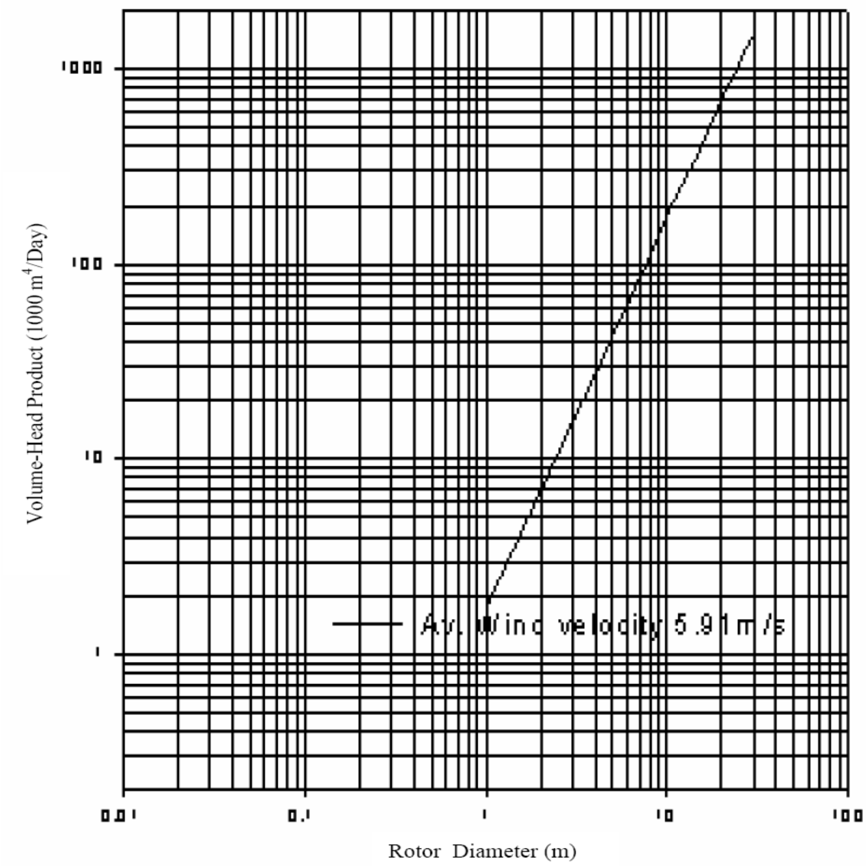


Figure 7.3: Wind Pump Rotor Sizing Nomogram for Patenga, Bangladesh

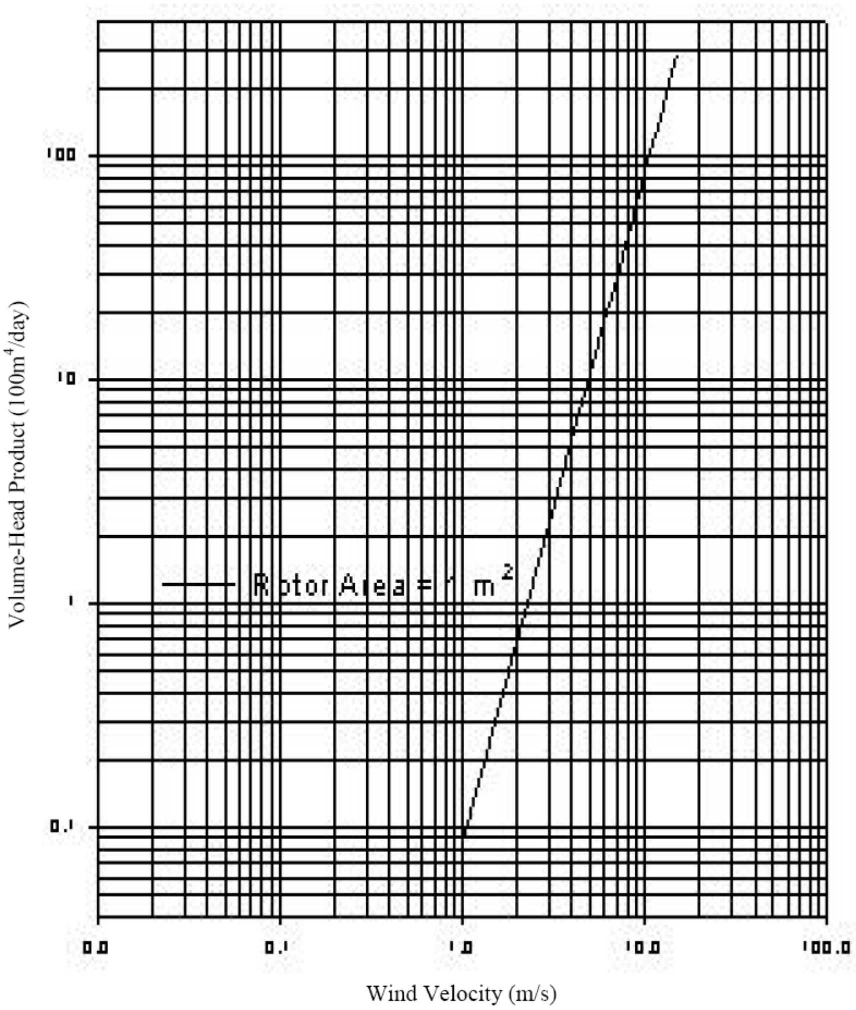


Figure 7.4: Nomogram for Wind Pump Rotor Sizing

7.8 Conclusion for wind power for rural areas of Bangladesh

There is a prospective site of wind electricity generation in many places of Bangladesh, namely, Patenga, Thakurgaon, Jessore etc. The wind data at different locations also show similar strength of wind energy. The installation of wind power machines at the coastal and island areas will be useful for lifting water and for generation of electricity. Wind pumping could play a significant role in the supply of water for irrigation and drinking in the rural areas of developing countries.

Bangladesh is neither rich in commercial resources of energy nor progressing satisfactorily in the area of wind energy. Since, the prospects of wind energy in Bangladesh look promising we should engage international and national resources to harness energy from this renewable energy source. It is the appropriate time to expand research and development in the area of wind energy utilization for daily life.

7.9 Wind Power Project by Bangladesh Power Development Board (BPDB)

7.9.1 Wind Battery Hybrid Power Project at Kutubdia Island, Cox's Bazar District (Bay of Bengal)

Bangladesh Power Development Board (BPDB) implemented the 1000 kWp capacity Wind Battery Hybrid Power Project (WBHPP) at the Kutubdia Island (Bay of Bengal) in the Cox's Bazar District.

Under this project, total 50 numbers of 20kWp capacity Stand Alone Type Wind Turbines are being installed at Taboler Char areas of the Ali Akber Dell Union Parisahd of Kutubdia Upazilla. The total capacity of all the wind turbines is 1000 kWp(1 MW). The Wind turbines producing electricity which being stored in battery bank. The entire system tailed as Wind Battery Hybrid Power Plant (WBHPP). This project being installed on turn-key basis at Kutubdia, Cox's Bazar, Bangladesh.

The wind turbines produce electricity and charges the batteries at battery banks which consisting of 1000 numbers of 200AH with capacity of 12VDC. The stored electrical power from the battery banks being converted to AC (Alternative Current) by using inverters and distributed to the consumers through overhead power cable. This supply system exactly having 3-phase, On-Grid form and matches with conventional power AC system and loads.

For the conversion of the DC power from the batteries, total 8 numbers of 150KW capacity each inverter has been installed. These inverters give pure sine wave output. These 8 numbers of inverters have been synchronized and paralleled. So the load out put on the system is shared by all these 8 numbers of inverters. The synchronized outputs from all these 8 numbers of inverters are put together in a common bus-bar LT pane. From the common bus-bar the totaled 3-ϕ output is supplied to the LT side of a 630KVA, 0.415KV/11KV step-up transformer.

The 11KV output is taken away from the project site area to the Barghop Bazar which is about 8 km away from the project control room. This 11KV power is distributed throughout the consumers of the Kutubdia Upazilla Sadar through the 11KV/0.415KV step down transformers and the distribution lines.

Figure 7.5: Wind Turbines of 1000 kWp Capacity Wind Battery Hybrid Power Project at Kutubdia Island

Figure 7.6: Anemometers and Wind Turbines of 1000 kWp Capacity Wind Battery Hybrid Power Project

Figure 7.7: Control room of 1000 kWp Capacity Wind Battery Hybrid Power Project at Kutubdia Island

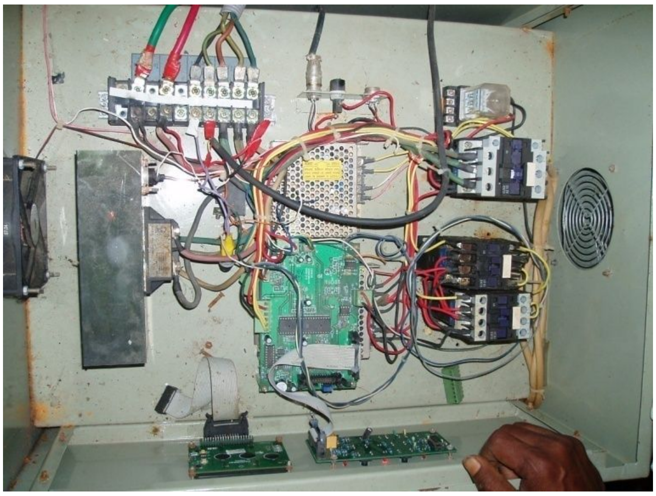


Figure 7.8: Converter of 1000 kWp Capacity Wind Battery Hybrid Power Project at Kutubdia Island

Figure 7.9: Battery Bank of 1000 kWp Capacity Wind Battery Hybrid Power Project at Kutubdia Island

Figure 7.10: Inverter of 1000 kWp Capacity Wind Battery Hybrid Power Project at Kutubdia Island

Figure 7.11: Overhead grid distribution line of 1000 kWp Capacity Wind Battery Hybrid Power Project

7.9.2 Grid Connected Wind Energy Project at Muhuri Dam areas by BPDB

BPDB has implemented a pilot project of 0.90 MW capacity of the Grid Connected Wind Energy (GCWE) at the Muhuri Dam Areas in the Feni distrct in 2004. The installation, commissioning and erection works of 4 units of the 225 kWp GCWE turbines at this site had been completed in 2004. This is the first ever Grid Connected Wind Energy project in Bangladesh. The grid connected wind turbines generate electricity at 440V. This is stepped up by the 0.440KV/11KV step-up transformers at the fed into the nearly 11KV distribution lines.

Thus generating electricity from wind in the coastal areas can be transmitted to other regions of the country through the high voltage transmission lines. Very little operation and maintenance will be required during the whole life time of wind turbines and no fuel will be required for generating electricity from wind.

Figure 7.12: Pilot project of 0.90 MW capacity of the Grid Connected Wind turbines in the Muhuri Dam areas at Feni District

Figure 7.13: Step up transformer in Pilot project of 0.90 MW capacity of the Grid Connected Wind turbines in the Muhuri Dam areas at Feni District

7.9.3 Future Plan of BPDB for wind turbine

BPDB established a Wind Resource Assessment Station (WRAS) at the Moghnama Ghat under Cox's Bazar district is being started. The installation, commissioning, erection, testing etc. works of this WRAS have been completed in December 2003. Wind monitoring by this WRAS has been started in December 2003. So far wind resource data of 5 months of this site have been gathered and these data shows the clear viability of Grid Connected Wind Energy at this site. BPDB is planning for another 0.90 MW pilot project at this site. The pilot for this site is expected to be implemented very soon. Another WRAS installation at Kuakhata is under process to measure the wind potential at that location.

7.9.4 Wind energy installation under renewable Energy Programme (REP)

Energy Resource: Wind Turbine, Type of installation: Water pumping wind mill Irrigation, No of installation: 1, Capacity of installation: 1X1.0 kWp, 3X1.5 kWp, 1X10 kWp and Location of Installation: Patenga (Coastal Area), Chittagong. Functional Status: Functioning

Energy Resource: Wind, Type of installation: Resource Assessment, Location of Installation: Coastal Districts, Total installation by BPDB = 2 MW

7.9.5 Wind Resource Assessment Station at Feni

BPDB installed a 160 feet tower at the Muhuri Dam site in the Feni district in May 2003. Two high resolution Anemometers were installed on this tower, one Anemometer at 80 feet and the other at 160 feet height. One Wind Vane has been installed at 80 feet height.

The average wind speed, till to date, at the Muhuri Dam areas is 6.50 m/s. For the financial viability of the Grid Connected Wind Turbines, the required annual average wind speed is 6 m/s. So, the wind speeds of the Muhuri Dam areas are encouraging for the grid connected wind energy projects at the project site areas of the Muhuri Dam in the Feni district. The site area is large enough for the larger Wind Energy Projects. The grid is within 0.50 km from the site. The project site is also connected by concrete roads. For all these reasons, the project site area emerges as one of the most suitable areas for grid connected wind farm in Bangladesh.

Studying the pattern of wind blowing over Bangladesh, it has been discovered that the peak windy season of a year coincides with the peak demand for electricity of the country. So, generating electricity from wind with the Grid Connected Wind Turbines, can contribute greatly to cater the increased demand during summer peak season.

7.9.6 Wind Resource Assessment Station at Moghnama Ghat, Cox's Bazar

BPDB also installed another Wind Resource Assessment Station (WRAS) at the Mognamaghat site in the Cox's Bazar District. The Installation, commissioning, erection, testing etc. works of this WRAS were completed in December 2003. Wind monitoring by this WRAS started in December 2003. The annual average wind speed at this site is also more than 6.5 m/s.

The site area is large enough for the larger Wind Energy Projects. The grid is within 10 km from the site. The project site is also connected by concrete roads. For all these reasons, the project site area emerges as one of the most suitable areas for grid connected wind farm in Bangladesh.

8

World Wide Wind Power

8.1 Global annual installed Capacity 1996-2007

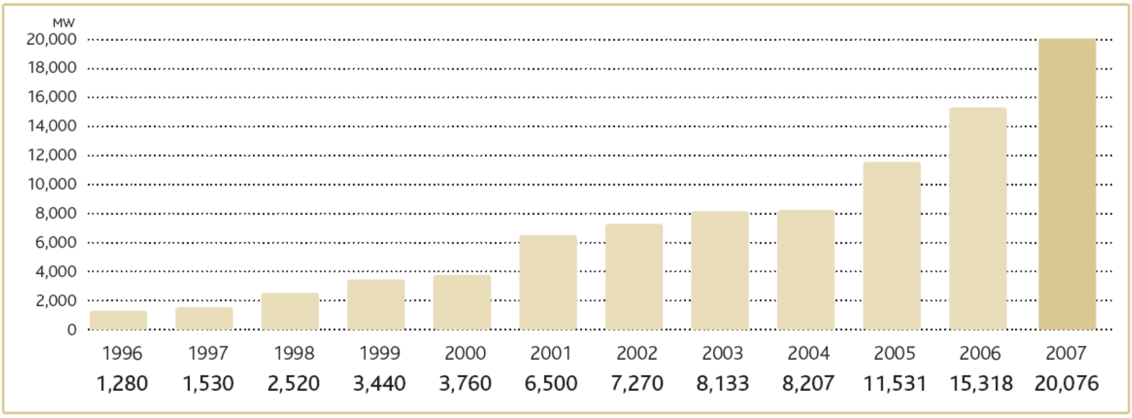


Figure 8.1: Global annual installed capacity in MW

8.2 Annual installed Capacity by region 2003-2007

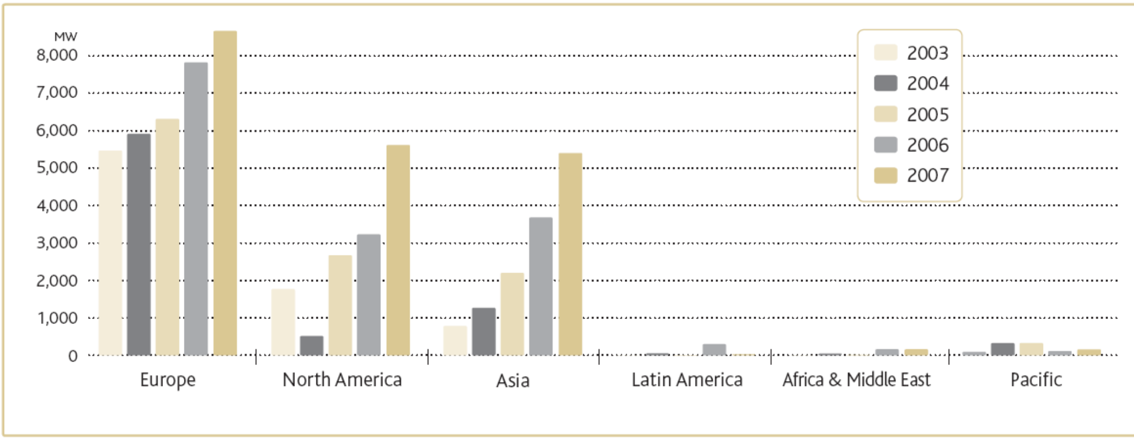


Figure 8.2: Annual installed Capacity by region 2003-2007

8.3 Global installed wind power capacity (mw) – regional distribution

Table 8.1: Global installed wind power capacity (MW) – regional distribution

		Revised end 2006	New 2007	Total end 2007
AFRICA & MIDDLE EAST	Egypt	230	80	310
	Morocco	64	60	124
	Iran	48	19	67
	Tunisia	20	0	20
	Other [1]	16	1	17
	Total	**378**	**160**	**538**
ASIA	India	6,270	1,730	8,000
	China	2,604	3,449	6,050
	Japan	1,394	139	1,538
	Taiwan	188	100	282
	South Korea	173	18	191
	Philippines	25	0	25
	Other [2]	5	0	5
	Total	**10,659**	**5,436**	**16,091**
EUROPE	Germany	20,622	1,667	22,247
	Spain	11,623	3,522	15,145
	Denmark	3,136	3	3,125
	Italy	2,123	603	2,726
	France	1,567	888	2,454
	UK	1,962	427	2,389
	Portugal	1,716	434	2,150
	Netherlands	1,558	210	1,746
	Austria	965	20	982
	Greece	746	125	871
	Ireland	746	59	805
	Sweden	571	217	788
	Norway	325	8	333
	Belgium	194	93	287
	Poland	153	123	276
	Rest of Europe [3]	556	263	812
	Total Europe	**48,563**	**8,662**	**57,136**
	of which EU-27 [4]	*48,069*	*8,554*	*56,535*
LATIN AMERICA & CARIBBEAN	Brazil	237	10	247
	Mexico	87	0	87
	Costa Rica	74	0	74
	Caribbean (w/o Jamaica)	35	0	35
	Argentina	27	2	29
	Colombia	20	0	20
	Jamaica	20	0	20
	Chile	2	18	20
	Cuba	5	0	5
	Total	**507**	**30**	**537**
NORTH AMERICA	USA	11,575	5,244	16,818
	Canada	1,460	386	1,846
	Total	**13,035**	**5,630**	**18,664**
PACIFIC REGION	Australia	817	7	824
	New Zealand	171	151	322
	Pacific Islands	12	0	12
	Total	**1,000**	**158**	**1,158**
	World total	**74,141**	**20,076**	**94,123**

Here,

1. Cape Verde, Israel, Jordan, Nigeria, South Africa;
2. Bangladesh, Indonesia, Sri Lanka;
3. Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Faroe Islands, Finland, Hungary, Iceland, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Norway, Romania, Russia, Slovakia, Slovenia, Switzerland, Ukraine;
4. Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, UK;

Please note: Project decommissioning of 93 MW and rounding affect the final sums

8.4 Wind power in India

The development of wind power in India began in the 1990s, and has significantly increased in the last few years. Although a relative newcomer to the wind industry compared with Denmark or the US, a combination of domestic policy support for wind power and the rise of Suzlon (a leading global wind turbine manufacturer) have led India to become the country with the fourth largest installed wind power capacity in the world, and the wind energy leader in the developing world.

As of November 2008 the installed capacity of wind power in India was 9587.14 MW, mainly spread across Tamil Nadu (4132.72 MW), Maharashtra (1837.85 MW), Karnataka (1184.45 MW), Rajasthan (670.97 MW), Gujarat (1432.71 MW), Andhra Pradesh (122.45 MW), Madhya Pradesh (187.69 MW), Kerala (23.00 MW), West Bengal (1.10 MW), other states (3.20 MW). It is estimated that 6,000 MW of additional wind power capacity will be installed in India by 2012. Wind power accounts for 6% of India's total installed power capacity, and it generates 1.6% of the country's power.

8.4.1 Overview

India has the world's fourth largest wind power industry, with an annual power production of 8,896 MW. Shown here is a wind farm in Kayathar, Tamil Nadu.

The worldwide installed capacity of wind power reached 93,849 MW by the end of 2007. Germany (22,247 MW), USA (16,818 MW), and Spain (15,145 MW) are ahead of India in fourth position. The short gestation periods for installing wind turbines, and the increasing reliability and performance of wind energy machines has made wind power a favored choice for capacity addition in India.

Suzlon, an Indian-owned company, emerged on the global scene in the past decade, and by 2006 had captured almost 8 percent of market share in global wind turbine sales. Suzlon is currently the leading manufacturer of wind turbines for the Indian market, holding some 52.4 percent of market share in India. Suzlon's success has made India the developing country leader in advanced wind turbine technology.

8.4.2 Tamil Nadu (4132.72 MW)

India is keen to decrease its reliance on fossil fuels to meet its energy demand. Shown here is a wind farm in Muppandal, Tamil Nadu.

Tamil Nadu is the state with most wind generating capacity: 4132.72 MW at the end of 2008. Not far from Aralvaimozhi, the Muppandal wind farm which the largest in Asia is located near the once impoverished village of Muppandal, supplying the villagers with electricity for work. The village had been selected as the showcase for India's $2 billion clean energy program which provides foreign companies with tax breaks for establishing fields of wind turbines in the area. In February 2009, Shriram EPC bagged INR 700 million contract for setting up of 60 units of 250 KW (totaling 15 MW) wind turbines in Tirunelveli district by Cape Energy.

8.4.3 Maharashtra (1837.85 MW)

Maharashtra is second only to Tamil Nadu in terms of generating capacity. Suzlon has been heavily involved. Suzlon operates what was once Asia's largest wind farm, the Vankusawade Wind Park (201 MW), near the Koyna reservoir in Satara district of Maharashtra.

8.4.4 Gujarat (1432.71 MW)

Samana in Rajkot district is set to host energy companies like China Light Power (CLP) and Tata Power have pledged to invest up to Rs.8.15 billion ($189.5 million) in different projects in the area. CLP, through its India subsidiary CLP India, is investing close to Rs.5 billion for installing 126 wind turbines in Samana that will generate 100.8 MW power. Tata Power has installed wind turbines in the same area for generating 50 MW power at a cost of Rs.3.15 billion. Both projects are expected to become operational by early next year, according to government sources. The Gujarat government, which is banking heavily on wind power, has identified Samana as an ideal location for installation of 450 turbines that can generate a total of 360 MW. To encourage investment in wind energy development in the state, the government has introduced a raft of incentives including a higher wind energy tariff. Samana has a high tension transmission grid and electricity generated by wind turbines can be fed into it. For this purpose, a substation at Sadodar has been installed. Both projects are being executed by Enercon Ltd, a joint venture between Enercon of Germany and Mumbai-based Mehra group.

ONGC Ltd has commissioned its first wind power project. The 51 MW project is located at Motisindholi in Kutch district of Gujarat. ONGC had placed the EPC order on Suzlon Energy in January 2008, for setting up the wind farm comprising 34 turbines of 1.5-mw each. Work on the project had begun in February 2008, and it is learnt that the first three turbines had begun production within 43 days of starting construction work. Power from this Rs 308 crore captive wind farm will be wheeled to the Gujarat state grid for onward use by ONGC at its Ankleshwar, Ahmedabad, Mehsana and Vadodara centres. ONGC has targeted to develop a captive wind power capacity of around 200 MW in the next two years.

8.4.5 Karnataka (1184.45 MW)

There are a lot of small wind farms in Karnataka. Karnataka is one of the states in India which has the most number of wind mill farms. Chitradurga, Gadag are some of the districts where there are a large number of Windmills. Chitradurga alone has over 200 wind turbines.

8.4.6 Rajasthan (670.97 MW)

Jaisalmer has two wind power farms. Sikar District has one near hathsar.

8.4.7 Madhya Pradesh (187.69 MW)

Present Rs.3.97p/kwh coming down to Rs 3.30 from the 5th year to 20th year

In consideration of unique concept, Govt. of Madhya Pradesh has sanctioned another 15 MW project to MPWL at Nagda Hills near Dewas. All the 25 WEGs have been commissioned on 31.03.2008 and under successful operation. (http://www.windpowerindia.com/generation.htm). sfdsfadsfadsfadf

8.4.8 Kerala (23.00 MW)

The first wind farm of the state was set up at Kanjikode in Palakkad district. It has a generating capacity of 2.03 MW. A new wind farm project was launched with private participation at Ramakkalmedu in Idukki district. The project, which was inaugurated by chief minister V. S. Achuthanandan in April 2008, aims at generating 10.5 MW of electricity.

8.4.9 West Bengal (1.10 MW)

The total installation in West Bengal is just 1.10 MW as there was only 0.5 MW addition in 2006-2007 and none between 2007-2008 and 2008-2009 (till Nov 2008)

8.4.10 Others (3.20 MW)

In other states 3.20 MW is installed.

8.4.11 Utilization

Despite the high installed capacity, the actual utilization of wind power in India is low because policy incentives are geared towards installation rather than operation of the plants. This is why only 1.6% of actual power production in India comes from wind although the installed capacity is 6%. The government is considering the addition of incentives for ongoing operation of installed wind power plants.

8.5 Wind power in Sri Lanka

Using wind for power generation is not very common in Sri Lanka. Presently a 3 MW wind power plant is in operation in operation in the South of Sri Lanka. Sri Lanka has had, however, less than a decade of experience of generating electricity from wind. A community based wind system of 2.5 kW was first commissioned in 1998 as a hybrid with a diesel generator set and a biogas unit. This wind system was imported from Europe. By the year 2001, Sri Lanka commenced producing her own small wind generators with specialized technical and design inputs from local and European experts. These interventions are facilitated by Practical Application (ITDG)

Some improvements have been made in the recent past to the Practical Action's (ITDG) wind systems. Practical Action has carried out some research into improving charge controllers. The circuits relied on relays in the past have now been replaced with electronic components. Further, the problems with shearing of tail vanes are handled by hinging instead of riveting, which was another improvement which was made. Wind systems installed on the coast face corrosion problems. Galvanising them to reduce corrosion adds more costs to the overall system.

Some other recent interventions have been to introduce 3 more local designs. National Engineering Research and Development Centre of Sri Lanka has designed a 100W small wind system, which are being tested in collaboration with the Practical Action at one of Practical Action's(ITDG) small wind systems clusters. A technology transfer programme on the same design is in the pipeline, to be held in November and December in Sri Lanka. Another 2 designs have been developed by Practical Action in association with the Resource Management Associates led by Mr. Sunith Fernando, one of the pioneer designers of Small Wind Systems. One is a wind- solar 150W / 24W hybrid system while the other is a 250W system. These are being tested in one of the small wind systems clusters in Hambantota district. The fabrication and testing on this was held in Nepal and India with Practical Action – Nepal and the Indian Wind Energy Association. UNDP GEF SGP, SARI/Energy with Winrock International and Energy Conservation Fund of Sri Lanka has supported these recent interventions.

A major requirement for sustainability of any technology is the financing and after sales services despite a high quality product being provided. Revolving credit schemes in communities to partially finance the systems have proved to work well. The current model, necessitates the users to purchase the battery and attend to the wiring aspects. The wind system with the inverter is provided as a grant cum loan to some selected communities on a pilot basis. The grant accounts to 65% of the costs and the loan is to be settled between 2-3 years. The loan repayment rentals are collected into the revolving fund to grant fresh loans to others. Monitoring and after sales service are supported by training local technicians to attend to these needs. However, the low business volumes and longer travel distances has predominantly barred the effectiveness of this approach.

The future of the stand alone domestic type electricity generation from small wind turbines displays a huge potential. To deal with fluctuating wind patterns hybriding with solar, wave, biogas and other forms of renewable energy sources are also being explored.

8.6 Wind power in Pakistan

Pakistan is building wind power plants Gharo, Keti Bandar and Bin Qasim in Sindh. The government of Pakistan decided to develop wind power energy sources due to problems supplying energy to the southern coastal regions of Sindh and Balochistan, the project was undertaken with assistance from the government of China. Another area with potential is Swat which shows good wind conditions and whose traditional leader Swat (princely state) Miangul Adnan Aurangzeb works with investors interested in windpower investment there once local political conditions improve.

Five wind turbines in Jhimpir, 70km from Karachi are being developed by Zorlu Enerji Pakistan. Total cost of the project is $110 million. Zorlu Enerji reported to had completed five wind turbines in Jhimpir, each capable of producing 1.2 megawatts of electricity. Though initially 6MW of electricity will be produced by the company, the project will be expanded to 50MW in the next few years. In October 15, 2008, a Turkish company was reportedly close to completing the first windmill in Pakistan.

8.5.1 Gharo Wind Power Plant

Gharo Wind Power Plant is planned to be built in the persistently wind-swept corridor of Gharo, Sindh, Pakistan. This will be one of the first wind power projects in Pakistan.

The turbine manufacturer Fuhrländer of Germany and Access Energy Inc of United States have signed an agreement with Alternative Energy Development Board (AEDB) of Pakistan, to manufacture wind turbines in Pakistan to help establish wind power projects. US-based Access Energy would finance the project to set up a 50 MW wind power plant along the general wind corridor in Gharo, while the German Company, Fuhrländer, would transfer the technology to Pakistan for manufacturing of wind turbines along with its accessories to set up a minimum of 1000 MW power plants. Halcrow Pakistan has compiled the Enivoronmental Impact Assessment for this project.

9

Environmental Effects of Wind Power

9.1 Introduction

Compared to the environmental effects of traditional energy sources, the environmental effects of wind power are relatively minor. Wind power consumes no fuel, and emits no air pollution, unlike fossil fuel power sources. The energy consumed to manufacture and transport the materials used to build a wind power plant is equal to the new energy produced by the plant within a few months of operation. Garrett Gross, a scientist from UMKC in Kansas City, Missouri states, "The impact made on the environment is very little when compared to what is gained." The initial carbon dioxide emission from energy used in the installation is "paid back" within about 9 months of operation for offshore turbines.

Danger to birds and bats has been a concern in some locations. However, studies show that the number of birds killed by wind turbines is negligible compared to the number that die as a result of other human activities, and especially the environmental impacts of using non-clean power sources. Bat species appear to be at risk during key movement periods. Almost nothing is known about current populations of these species and the impact on bat numbers as a result of mortality at windpower locations. Offshore wind sites 10 km or more from shore do not interact with bat populations. While a wind farm may cover a large area of land, many land uses such as agriculture are compatible, with only small areas of turbine foundations and infrastructure made unavailable for use.

Aesthetics have also been an issue in some areas. In the USA, the Massachusetts Cape Wind project was delayed for years mainly because of aesthetic concerns. In the UK, repeated opinion surveys have shown that more than 70% of people either like, or do not mind, the visual impact. According to a town councillor in Ardrossan, Scotland, the overwhelming majority of locals believe that the Ardrossan Wind Farm has enhanced the area, saying that the turbines are impressive looking and bring a calming effect to the town.

9.2 Carbon dioxide emissions and pollution

Wind power consumes no fuel for continuing operation, and has no emissions directly related to electricity production. Operation does not produce carbon dioxide, sulfur dioxide, mercury, particulates, or any other type of air pollution, as do fossil fuel power sources. Wind power plants consume resources in manufacturing and construction. During manufacture of the wind turbine, steel, concrete, aluminum and other materials will have to be made and transported using energy-intensive processes, generally using fossil energy sources. The initial carbon dioxide emissions "pay back" is within about 9 months of operation for off shore turbines.

9.3 Wind power may affect emissions at fossil-fuel plants used for reserve and regulation

It is sometimes said that wind energy, for example, does not reduce carbon dioxide emissions because the intermittent nature of its output means it needs to be backed up by fossil fuel plants. Wind turbines do not displace fossil generating capacity on a one-for-one basis. But it is unambiguously the case that wind energy can displace fossil fuel-based generation, reducing both fuel use and carbon dioxide emissions.

A study by the Irish national grid stated that "Producing electricity from wind reduces the consumption of fossil fuels and therefore leads to emissions savings", and found reductions in CO_2 emissions ranging from 0.33 to 0.59 tonnes of CO_2 per MWh.

9.4 Net energy gain

The energy consumed to manufacture and transport the materials used to build a wind power plant is equal to the new energy produced by the plant within a few months of operation. Garrett Gross, a scientist from UMKC in Kansas City, Missouri states, "The impact made on the environment is very little when compared to what is gained." The initial carbon dioxide emission from energy used in the installation is "paid back" within about 9 months of operation for off shore turbines. Any practical large-scale energy source must replace the energy used in its construction. The energy return on investment (EROI) for wind energy is equal to the cumulative electricity generated divided by the cumulative primary energy required to build and maintain a turbine. The EROI for wind ranges from 5 to 35, with an average of around 18. EROI is strongly proportional to turbine size,[6] and larger late-generation turbines are at the high end of this range, at or above 35. Since energy produced is several times energy consumed in construction, there is a net energy gain. The energy used for construction is produced by the wind turbine within a few months of operation.

9.5 Ecological footprint

Figure 9.1: Over a dozen wind turbines are visible on the horizon near an open-pit coal mine in Germany

Unlike fossil fuel and nuclear power stations, which circulate or evaporate large amounts of water for cooling, wind turbines do not need water to generate electricity. However, leaking lubricating oil or hydraulic fluid running down turbine blades may be scattered over the surrounding area, in some cases contaminating drinking water areas.

Wind turbines avoid the sometimes drastic ecological impact of mining techniques to extract fossil fuels, such as the open-pit mining used for shallow coal deposits and oil sands, and the sometimes extensive water pollution that results from processing low-grade fossil fuels.

Projects such as the Black Law Wind Farm have received wide recognition for its contribution to environmental objectives, including praise from the Royal Society for the Protection of Birds, who said that the scheme was not only improving the landscape in a derelict opencast mining site, but also benefiting a range of wildlife in the area, with an extensive habitat management projects covering over 14 square kilometers.

9.6 Climate change

One study reports simulations that show detectable changes in global climate for very high wind farm usage, on the order of 10% of the world's land area. In a similar way, there are concerns of micro-climate change, in particular for urban areas nearby, due to changed airflow and reduced wind power.

9.7 Land use

To reduce losses caused by interference between turbines, a wind farm requires roughly 0.1 km^2 (0.039 sq mi) of unobstructed land per megawatt of nameplate capacity. A 200 MW wind farm might extend over an area of approximately 20 km^2 (7.7 sq mi).

Clearing of wooded areas is often unnecessary. Farmers commonly lease land to companies building wind farms. In the U.S., farmers may receive annual lease payments of two thousand to five thousand dollars per turbine. The land can still be used for farming and cattle grazing. Less than 1% of the land would be used for foundations and access roads, the other 99% could still be used for farming.[14] Turbines can be sited on unused land in techniques such as center pivot irrigation. The clearing of trees around tower bases may be necessary for installation sites on mountain ridges, such as in the northeastern U.S.

Figure 9.2: In the United States, landowners typically receive $3,000 to $5,000 per year in rental income from each wind turbine, while farmers continue to grow crops or graze cattle up to the foot of the turbines.

Figure 9.3: A wind turbine at Greenpark, Reading, England, producing electricity for around one thousand homes

Turbines are not generally installed in urban areas. Buildings interfere with wind, turbines must be sited a safe distance ("setback") from residences in case of failure, and the value of land is high. However, there are a few notable exceptions. Toronto Hydro has built a lake shore demonstration project, and Steel Winds is a 20 MW urban project south of Buffalo, New York. Both of these projects are in urban locations, but benefit from being on uninhabited lake shore property.

Wind turbines located in agricultural areas may create concerns by operators of crop-dusting aircraft. Operating rules may prohibit approach of aircraft within a stated distance of the turbine towers; turbine operators may agree to curtail operations of turbines during crop-dusting operations.

In the UK there has also been concern about the damage caused to peat bogs, with one Scottish MEP campaigning for a moratorium on wind developments on peat lands saying that "Damaging the peat causes the release of more carbon dioxide than wind farms save".

Offshore locations use no land and avoid known shipping channels.

9.8 Impact on wildlife

9.8.1 Birds

Danger to birds is often the main complaint against the installation of a wind turbine. However, studies show that the number of birds killed by wind turbines is negligible compared to the number that die as a result of other human activities such as traffic, hunting, power lines and high-rise buildings, the introduction of feral and roaming domestic cats, and especially the environmental impacts of using non-clean power sources. For example, in the UK, where there are several hundred turbines, about one bird is killed per turbine per year; 10 million per year are killed by cars alone. In the United States, turbines kill 70,000 birds per year, compared to 80,000 killed by aircraft, 57 million killed by cars, 97.5 million killed by collisions with plate glass, and hundreds of millions killed by cats. An article in *Nature* stated that each wind turbine kills an average of 4.27 birds per year.

In the UK, the Royal Society for the Protection of Birds (RSPB) concluded that "The available evidence suggests that appropriately positioned wind farms do not pose a significant hazard for birds." It notes that climate change poses a much more significant threat to wildlife, and therefore supports wind farms and other forms of renewable energy. The National Audubon Society in the U.S. takes a similar position, broadly supporting wind power to help mitigate global warming, while cautioning against sitting wind farms in areas especially important to birds and other affected wildlife.

In some cases, the mere presence of wind turbines or transmission towers can affect threatened species, by restricting their range, thus fragmenting breeding populations. The U.S. Fish and Wildlife Service have issued voluntary guidelines for the sitting of wind energy facilities in the United States. These guidelines make recommendations regarding sitting which include avoiding placement in 1) areas documented as the location of any species protected under the Endangered Species Act, 2) in local bird migration pathways or areas where birds concentrate, 3) near landscape features that attract raptors, 4) in a configuration that is likely to cause bird mortality, and 5) where fragmentation of large contiguous tracts of wildlife habitat will occur as a result of turbine placement. The wind industry is resisting such regulations.

Some paths of bird migration, particularly for birds that fly by night, are unknown. A study suggests that migrating birds may avoid the large turbines, at least in the low-wind non-twilight conditions studied. A Danish 2005 (Biology Letters 2005:336) study showed that radio tagged migrating birds traveled around offshore wind farms, with less than 1% of migrating birds passing an offshore wind farm in Rønde, Denmark, got close to collision, though the site was studied only during low-wind non-twilight conditions.

The National Environmental Research Institute of Denmark developed a Thermal Animal Detection System (TADS), a heat-activated infrared video camera mounted on a wind turbine that records bird collisions. The first results, released in 2007, found "seabirds to be remarkably adept at avoiding offshore installations".

Figure 9.4: An early wind farm in the Tehachapi Mountains of California

A survey at Altamont Pass, California, conducted by a California Energy Commission in 2004 showed that onshore turbines killed between 1,766 and 4,721 birds annually (881 to 1,300 of which were birds of prey). According to a study by the National Research Council, the relatively high bird kills at Altamont Pass are due to the large numbers of older wind turbines there. Many of these older turbines have lower hub heights, shorter rotor diameters which spin at high RPM, and tighter turbine spacing than are typical for newer wind farms. Older turbines often have lattice towers that attract nesting birds, in contrast to newer turbines with tubular steel towers whose smooth exteriors provide no nesting purchase.

Radar studies of proposed onshore and near-shore sites in the eastern U.S. have shown that migrating songbirds fly well within the reach of turbine blades.

A wind farm in Norway's Smola islands is reported to have affected a colony of sea eagles, according to the British Royal Society for the Protection of Birds. Turbine blades killed ten of the birds between August 2005 and March 2007, including three of the five chicks that fledged in 2005. Nine of the 16 nesting territories appear to have been abandoned. Norway is regarded as the most important place for white-tailed eagles.

A study published in 2008 found that wind turbines on European farmland have only minimal effects on wintering farmland birds, and found no evidence that future expansion of wind farms on European farmland will be detrimental to birds, but cautioned that more work is needed.

9.8.2 Bats

The numbers of bats killed by existing onshore and near-shore facilities has troubled bat enthusiasts. A study in 2004 estimated that over 2200 bats were killed by 63 onshore turbines in just six weeks at two sites in the eastern U.S. This study suggests some onshore and near-shore sites may be particularly hazardous to local bat populations and more research is needed. Migratory bat species appear to be particularly at risk, especially during key movement periods (spring and more importantly in fall). Lasiurines such as the hoary bat, red bat, and the silver-haired bat appear to be most vulnerable at North American sites. Almost nothing is known about current populations of these species and the impact on bat numbers as a result of mortality at windpower locations. It has been suggested that bats are attracted to these structures in search of roosts. Offshore wind sites 10 km (6 mi) or more from shore do not interact with bat populations.

Bats may be injured by direct impact with turbine blades, towers, or transmission lines. Recent research shows that bats may also be killed when suddenly passing through a low air pressure region surrounding the turbine blade tips. The low pressure damages the bat's lungs, called *barotrauma*. Birds have more rigid lungs and are not affected by the low pressure zone.

In October 2008, the Bats and Wind Energy Cooperative began a study to test the effect on bats of stopping wind farm operations during low wind conditions, when bats are most active.

9.8.3 Fish

In Ireland, construction of a wind farm caused pollution feared to be responsible for wiping out vegetation and fish stocks in Lough Lee. A separate landslide is thought to have been caused by wind farm construction, and has killed thousands of fish by polluting the local rivers with sediment.

9.9 Offshore

Many offshore wind farms are being built in UK waters. In January 2009, a comprehensive government environmental study of coastal waters in the United Kingdom concluded that there is scope for between 5,000 and 7,000 offshore wind turbines to be installed without an adverse impact on the marine environment. The study – which forms part of the Department of Energy and Climate Change's Offshore Energy Strategic Environmental Assessment – is based on more than a year's research. It included analysis of seabed geology, as well as surveys of sea birds and marine mammals.

9.10 Safety

Operation of any utility-scale energy conversion system presents safety hazards. Wind turbines do not consume fuel or produce pollution during normal operation, but still have hazards associated with their construction and operation.

There have been at least 40 fatalities due to construction, operation, and maintenance of wind turbines, including both workers and members of the public, and other injuries and deaths attributed to the wind power life cycle. Most worker deaths involve falls or becoming caught in machinery while performing maintenance inside turbine housings. Blade failures and falling ice have also accounted for a number of deaths and injuries. Deaths to members of the public include a parachutist colliding with a turbine and small aircraft crashing into support structures. Other public fatalities have been blamed on collisions with transport vehicles and motorists distracted by the sight and shadow flicker of wind turbines along highways.

When a turbine's brake fails, the turbine can spin freely until it disintegrates or catches fire. Freely spinning blades may also hit the tower, causing collapse, as occurred on March 6, 2009, in Altona, New York. Turbine blades may fail spontaneously due to manufacturing flaws. Lightning strikes are a common problem, also causing rotor blade damage and fires. When ejected, pieces of broken blade and ice can be thrown hundreds of meters away. Although no member of the public has been killed by a malfunctioning turbine, there have been close calls, including injury by falling ice. Large pieces of debris, up to several tons, have dropped in populated areas, residential properties, and roads, damaging cars and homes.

Often turbine fires cannot be extinguished because of the height, and are left to burn themselves out. In the process, they generate toxic fumes and can scatter flaming debris over a wide area, starting secondary fires below. Several turbine-ignited fires have burned hundreds of acres of vegetation each, and one burned 800 square kilometres (200,000 acres) of Australian National Park.

Electronic controllers and safety sub-systems monitor many different aspects of the turbine, generator, tower, and environment to determine if the turbine is operating in a safe manner within prescribed limits. These systems can temporarily shut down the turbine due to high wind, electrical load imbalance, vibration, and other problems. Recurring or significant problems cause a system lockout and notify an engineer for inspection and repair. In addition, most systems include multiple passive safety systems that stop operation even if the electronic controller fails.

Wind power proponent and author Paul Gipe estimated in Wind Energy Comes of Age that the mortality rate for wind power from 1980–1994 was 0.4 deaths per terawatt-hour. Paul Gipe's estimate as of end 2000 was 0.15 deaths per TWh, a decline attributed to greater total cumulative generation.

By comparison, hydroelectric power was found to have a fatality rate of 0.10 per TWh (883 fatalities for every TW·yr) in the period 1969–1996. This includes the Banqiao Dam collapse in 1975 that killed thousands. Although the wind power death rate is higher than some other power sources, the numbers are necessarily based on a small sample size. The apparent trend is a reduction in fatalities per TWh generated as more generation is supplied by larger units.

9.11 Aesthetics

Figure 9.5: Windmills at La Mancha, Spain, made famous by the 1605 novel *Don Quixote*, are a national treasure.

Historical experience of noisy and visually intrusive wind turbines may create resistance to the establishment of land-based wind farms. Residents near turbines may complain of "shadow flicker" caused by rotating turbine blades. Wind towers require aircraft warning lights, which create bothersome light pollution. Complaints about these lights have caused the FAA to consider allowing fewer lights per turbine in certain areas. These effects may be countered by changes in wind farm design.

Newer wind farms have larger, more widely spaced turbines, and so look less cluttered than old installations.

Aesthetic issues are important for onshore and near-shore locations in that the "visible footprint" may be extremely large compared to other sources of industrial power (which may be sited in industrially developed areas). Wind farms may be close to scenic or otherwise undeveloped areas. Constructing offshore wind developments at least 10 km from shore may reduce this concern. Aesthetic issues are subjective, however. Some people find wind farms pleasant and optimistic, or symbols of energy independence and local prosperity, and recognize that perceptions of what is "beautiful" in landscape is subject to change. While some tourism officials predict wind farms will damage tourism, some wind farms have themselves become tourist attractions, with several having visitor centers at ground level or even observation decks atop turbine towers.

9.12 Noise level

Modern large turbines have low sound levels at ground level. For example, in December 2006, a Texas jury denied a noise pollution suit against FPL Energy, after the company demonstrated that noise readings were not excessive. The highest reading was 44 decibels, which was characterized as about the same level as a 10 mile/hour (16 km/h) wind. In the United States, roadway noise contributes more to environmental noise exposure than any other noise source.

9.13 Community debate

Figure 9.6: The wind turbines at Findhorn Ecovillage which make the community a net exporter of electricity.

Figure 9.7: U.S. Landowners typically receive $3,000 to $5,000 per year in rental income from each wind turbine, while farmers continue to grow crops or graze cattle up to the foot of the turbines.

Figure 9.8: Wind turbines such as these, in Cumbria, England, have been opposed for a number of reasons, including aesthetics, by some sectors of the population.

Figure 9.9: Sheep graze before the Ardrossan Wind Farm

Many wind power companies work with local communities to reduce environmental and other concerns associated with particular wind farms. In other cases there is direct community ownership of wind farm projects. Appropriate government consultation, planning and approval procedures also help to minimize environmental risks. Some people may still object to wind farms but, according to The Australia Institute, their concerns should be weighed against the need to address the threats posed by climate change and the opinions of the broader community. Surveys of public attitudes across Europe and in many other countries show strong public support for wind power.

In Germany, for example, hundreds of thousands of people have invested in citizens' wind farms across the country and thousands of small and medium sized enterprises are running successful businesses in a new sector that in 2008 employed 90,000 people and generated 8 percent of Germany's electricity. Wind power has gained very high social acceptance in Germany.

In America, wind projects are reported to boost local tax bases, helping to pay for schools, roads and hospitals. Wind projects also revitalize the economy of rural communities by providing steady income to farmers and other landowners.

The Intrepid Wind Farm, in Iowa, is an example of one wind farm where the environmental impact of the project has been minimized through consultation and co-operation:

"Making sure the wind farm made as gentle an environmental impact as possible was an important consideration. Therefore, when MidAmerican first began planning the Intrepid site, they worked closely with a number of state and national environmental groups. Using input from such diverse groups as the Iowa Department of Natural Resources, the Nature Conservancy, Iowa State University, the U.S. Fish and Wildlife Service, the Iowa Natural Heritage Foundation, and the Iowa Chapter of the Sierra Club, MidAmerican created a statewide map of areas in the proposed region that contained specific bird populations or habitats. Those areas were then avoided as site planning got underway in earnest. In order to minimize the wind farm's environmental impact even further, MidAmerican also worked in conjunction with the Army Corp of Engineers, to secure all necessary permits related to any potential risk to wetlands in the area. Regular inspections are also conducted to make certain that the wind farm is causing no adverse environmental impact to the region."

9.13.1 The other examples

- January 29, 1997: Baywind Energy Co-operative began operating a 2.5 megawatt five-turbine wind farm near Ulverston, Cumbria. It was the first co-operative to own wind turbines in the United Kingdom. It has raised two million pounds and has 1,300 members. A proportion of the profits are invested in local community environmental initiatives through the Baywind Energy Conservation Trust.
- June 29, 2003: After the Cape Wind project was proposed several miles off the coast of Cape Cod, some people raised objections, including U.S. Senator Ted Kennedy who owns a summer home in the area.[83] But attitudes to the proposed wind farm have become more positive in recent years. A 2007 public opinion survey found that more than four out of five Massachusetts residents (84 percent) -- including 58 percent of those who live on the Cape -- explicitly supported the proposed Cape Wind offshore wind farm.
- On October 16, 2003 in Galway, Ireland, construction of the foundation of a wind farm caused almost half a square kilometer of bog to slide 2.5 kilometers down a hillside. The slide destroyed an unoccupied farmhouse and blocked two roads. Nearby residents expressed concern over these environmental impacts.

- On January 12, 2004, it was reported that the Center for Biological Diversity filed a lawsuit against wind farm owners for killing tens of thousands of birds at the Altamont Pass Wind Resource Area near San Francisco, California. In February 2008, a state appeals court upheld an earlier ruling that rejected the lawsuit.
- January 21, 2005: Three wind turbines on the island of Gigha in Scotland generate up to 675 kW of power. Revenue is produced by selling the electricity to the grid via an intermediary called Green Energy UK. Gigha residents control the whole project and profits are reinvested in the community. Local residents call the turbines "The Three Dancing Ladies".
- On December 4, 2007, environmentalists filed lawsuits to block two proposed wind farms in southern Texas. The lawsuits expressed concerns over wetlands, habitat, endangered species and migratory birds. In August 2008, a federal court judge dismissed the lawsuit, clearing the way for the completion of the wind farms by the end of 2008.
- On December 7, 2007, it was reported that some environmentalists opposed a plan to build a wind farm in western Maryland But other local environmentalists say that the environmental effects of wind farms "pale in comparison to coal-burning generators, which add to global warming and lead to acid rain" that is killing trees in the same area.
- On February 4, 2008, according to British Ministry of Defence turbines create a hole in radar coverage so that aircraft flying overhead are not detectable. In written evidence, Squadron Leader Chris Breedon said: "This obscuration occurs regardless of the height of the aircraft, of the radar and of the turbine."
- A February 21, 2008 article in Scoop reported on environmentalist opposition to a proposed wind farm in New Zealand.
- An April 16, 2008 article in the Pittsburgh Post-Gazette said that three different environmental organizations had raised objections to a proposed wind farm at Shaffer Mountain in northeastern Somerset County, Pennsylvania, because the wind farm would be a threat to the Indiana bat, which is listed as an endangered species.
- July 25, 2008: The Australian Hepburn Wind Project is a proposed wind farm, which will be the first Australian community-owned wind farm. The initiative emerged because the community felt that the state and federal governments were not doing enough to address climate change.
- August 12, 2008: The Ardrossan Wind Farm in Scotland has been "overwhelmingly accepted by local people". Instead of spoiling the landscape, they believe it has enhanced the area: "The turbines are impressive looking, bring a calming effect to the town and, contrary to the belief that they would be noisy, we have found them to be silent workhorses".
- A March 8, 2009 article in the Hawaii Free Press reported on an environmentalist organization called Maui Tomorrow that was against a proposed off-shore wind farm between O'ahu and Moloka'i.
- March 22, 2009: Some rural communities in Alberta, Canada want wind power companies to be allowed to develop wind farms on leased Crown land.

10

Conclusion

Sustainable energy is closely related to sustainable development; it is not exactly possible to make the development process sustainable unless the energy production, distribution and utilization are ensured to be sustainable. In fact, the notion of sustainable energy had been derived from the concept of sustainable development. Utilization of energy is very vital for development. The developed world utilizes much more energy than the developing countries. The least amount of gross energy is used by the third world poor countries. The utilization of more energy is positively correlated with the economic growth. Thus energy harnessing and utilization is a good indicator of development. But when energy use surpasses the sustainable level, the development will not sustain, it will collapse.

In Bangladesh about 30 percent of households are connected to electricity system, there is a huge potential demand for electricity compared to the current amount that is now being served. Also among the connected consumers, there are unserved demands. The market cannot be served now because of generation and infrastructure constraints. BPDB has limited capacity of financing new generation or transmission lines. Complicating the supply side even further is the availability of foreign exchange to pay for electricity supplied by present and future IPPs, PSCs and other energy related capital investments. Examination of the existing committed and planned generation plants reveals that generation would lag behind potential demand. The United Nations Commissions on Human Settlements forecast that the population of Dhaka would increase by almost 50 percent to become the sixth largest city in the world by 2010. With this increase, power generation would be insufficient to meet the demand.

Wind power is the most economic renewable source for large scale electric generation in recent years. The wind power capacity in the U.S. and Europe are increasing rapidly .It is drawn that this project is feasible, good for the environment, and economically attractive. Wind can be a vital source of energy if properly utilized and exploited. But before high-end projects are implemented, adequate research should be done to study the feasibility and determine a suitable type of project to implement. The primary parameter needed is wind speed and direction. Over the past years, many organizations have made many attempts to collect data on wind resources in Bangladesh. Based on this collected data, many small wind energy projects have been undertaken.

To make sure we have plenty of energy in the future, it's up to all of us to use energy wisely.

We must all conserve energy and use it efficiently. It's also up to those who will create the new energy technologies of the future.

All energy sources have an impact on the environment. Concerns about the greenhouse effect and global warming, air pollution, and energy security have led to increasing interest and more development in renewable energy sources such as solar, wind, geothermal, wave power and hydrogen.

Wind energy is an essential element for implementing sustainable development that gives people perpetual economic, social and environmental security. In practical field, Sustainable energy implies efficient use of conventional fossil fuels ensuring the least pollution with a future plan of permanent shift to renewable energy sources. Yet there are various barriers to promote Wind energy and there are also ways to overcome those. But we should start right now our journey to sustainable development through Wind energy; otherwise, it will be too late to protect the people and the planet.

We'll need to continue to use fossil fuels and nuclear energy until new, cleaner technologies can replace them.

"Imagination is more important than knowledge, for knowledge is limited, whereas imagination embraces the entire world - stimulating progress, giving birth to evolution".

- **Albert Einstein**

The future is ours, but we need energy to get there.

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