(Technology and Economics)

Wind Power

The wind is a source of free energy which has been used since ancient times in windmills for pumping water or grinding flour. The technology of high power, geared transmissions was developed centuries ago by windmill designers and the fantail wheel for keeping the main sales pointing into the wind was one of the world's first examples of an automatic control system.

Windmills at Kinderdijk in the Netherlands Dating from 1740 Used for Pumping Water from the Polder

Source - Birds As Art

Though modern technology has made dramatic improvements to the efficiency of windmills which are now extensively use for electricity generation, they are still dependent on the vagaries of the weather. Not just on the wind direction but on the intermittent and unpredictable force of the wind. Too little wind and they can't deliver sufficient sustained power to overcome frictional losses in the system. Too much and they are susceptible to damage. Between these extremes, cost efficient installations have been developed to extract energy from the wind.

Available Power From the Wind

- **Theoretical Power**

  The power **P** available in the wind impinging on a wind driven generator is given by:

  $$P = \tfrac{1}{2} C A \rho v^3$$

  where **C** is an efficiency factor known as the Power Coefficient which depends on the machine design, **A** is the area of the wind front intercepted by the rotor blades (the swept area), **ρ** is the density of the air (averaging 1.225 Kg/m^3 at sea level) and **v** is the wind velocity.

  Note that the power is proportional to area swept by the blades, the density of the air and to the cube of the wind speed. Thus doubling the blade length will produce four times the power and doubling the wind speed will produce eight times the power.

  Note also that the effective swept area of the blades is an annular ring, not a circle, because of the dead space around the hub of the blades.

  A similar equation applies to the theoretical power generated by a "run of river" and "tidal flow" hydro turbines.

Energy Conversion

- **Practical Power and Conversion Efficiency**

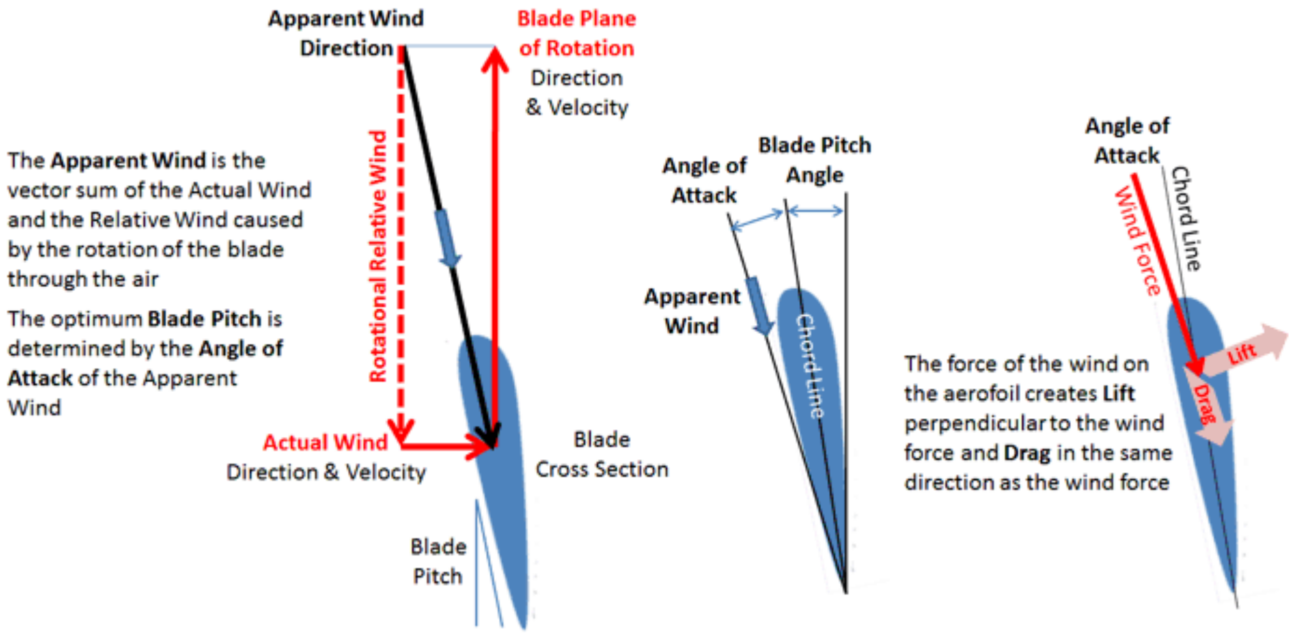
German aerodynamicist **Albert Betz** showed that a maximum of only 59.3% of the theoretical power can be extracted from the wind, no matter how good the wind turbine is, otherwise the wind would stop when it hit the blades. He demonstrated mathematically that the optimum occurs when the rotor reduces the wind speed by one third.

In practical designs, inefficiencies in the design and frictional losses will reduce the power available from the wind still further. Converting this wind power into electrical power also incurs losses of up to 10% in the drive train and the generator and another 10% in the inverter and cabling. Furthermore, when the wind speed exceeds the rated wind speed, control systems limit the energy conversion in order to protect the electric generator so that ultimately, the wind turbine will convert only about 30% to 35% of the available wind energy into electrical energy.

Note that the power output from commercially available domestic wind turbines is usually specified at a steady, gust free, wind speed of 12.5 m/s. (Force 6 on the Beaufort scale corresponding to a strong breeze). In many locations, particularly urban installations, the prevailing wind will rarely reach this speed.

- **Blade Design for Optimum Energy Capture**

Modern, high capacity wind turbines, such as those used by the electricity utilities in the electricity grid, typically have blades with a cross section similar to the aerofoils used to provide the lift in aircraft wings.



Turbine Blade Aerodynamics

The **Apparent Wind** is the vector sum of the Actual Wind and the Relative Wind caused by the rotation of the blade through the air

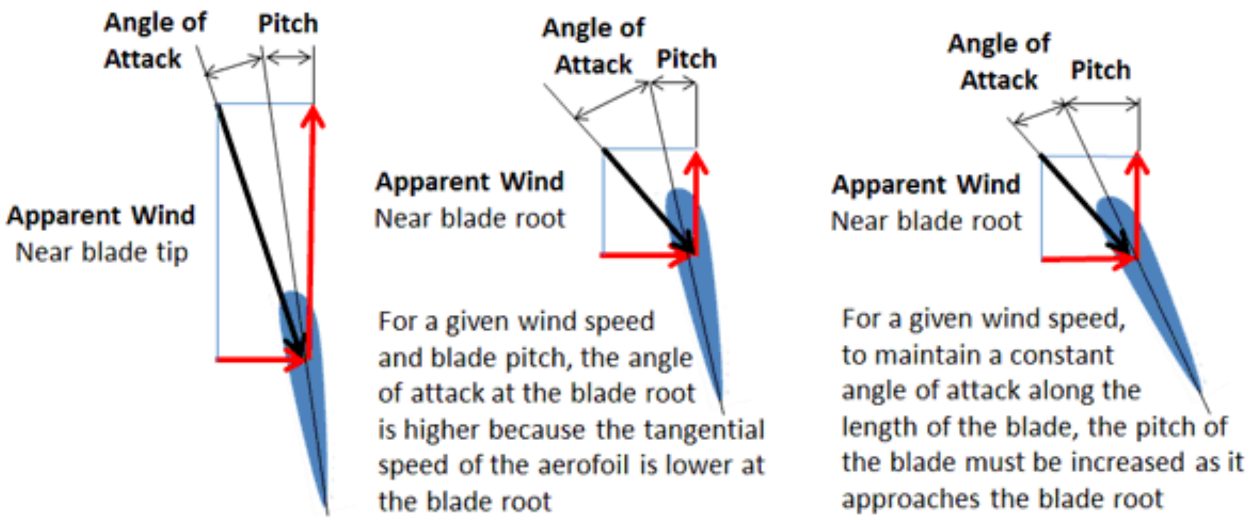
The optimum **Blade Pitch** is determined by the **Angle of Attack** of the Apparent Wind

The force of the wind on the aerofoil creates **Lift** perpendicular to the wind force and **Drag** in the same direction as the wind force

The direction of the apparent wind, that is the incident wind, relative to the chord line of the aerofoil is known as the **angle of attack**. Just as with aircraft wings, the lift resulting from the incident wind force increases as the angle of attack increases from 0 to a maximum of about 15 degrees at which point the smooth laminar flow of the air over the blade ceases and the air flow over the blade separates from the aerofoil and becomes turbulent. Above this point the lift force deteriorates rapidly while drag increases leading to a stall. See more about the angle of attack.

The tangential velocity **S** of any blade section at a distance **r** from the centre of rotation (the root of the blade) is given by $\mathbf{S} = \mathbf{r}\,\mathbf{\Omega}$ where $\mathbf{\Omega}$ is the angular velocity of rotation in radians.

For a given wind speed the apparent wind will be different at the root of the blade from the apparent wind at the tip of the blade because the rotational relative wind speed is different.



Angle of Attack and Blade Twist

For a given wind speed and blade pitch, the angle of attack at the blade root is higher because the tangential speed of the aerofoil is lower at the blade root

For a given wind speed, to maintain a constant angle of attack along the length of the blade, the pitch of the blade must be increased as it approaches the blade root

For a given speed of rotation, the tangential velocity of sections of the blade increases along the length of the blade towards the tip, so that the pitch of the blade must be twisted to maintain the same, optimum angle of attack at all sections along the length of the blade. The **blade twist** is thus optimised for a given wind speed. As the wind speed changes however, the twist will no longer be optimum. To retain the optimum angle of attack as wind speed increases a fixed pitch blade must increase its rotational speed accordingly, otherwise, for fixed speed rotors, variable pitch blades must be used.

The **number of blades** in the turbine rotor and its **rotational speed** must be optimised to extract the maximum energy from the available wind.

While using rotors with multiple blades should capture more wind energy, there is a practical limit to the number of blades which can be used because each blade of a spinning rotor leaves turbulence in its wake and this reduces the amount of energy which the following blade can extract from the wind. This same turbulence effect also limits the possible rotor speeds because a high speed rotor does not provide enough time for the air flow to settle after the passage of a blade before the next blade comes along.

There is also a lower limit to both the number of blades and the rotor speed. With too few rotor blades, or a slow turning rotor, most of the wind will pass undisturbed through the gap between the blades reducing the potential for capturing the wind energy. The fewer the number of blades, the faster the wind turbine rotor needs to turn to extract maximum power from the wind.

The notion of the **Tip Speed Ratio (TSR)** is a concept used by wind turbine designers to optimise a blade set to the shaft speed required by a particular electricity generator while extracting the maximum energy from the wind.

The tip speed ratio is given by:

$$\mathbf{TSR=\Omega R/V}$$

where **Ω** is the angular velocity of the rotor, **R** is the distance between the axis of rotation and the tip of the blade, and **V** is the wind speed.

A well designed typical three-bladed rotor would have a **tip speed ratio** of around 6 to 7.

- **Design Limits**

  For safety and efficiency reasons wind turbines are subject to operating limits depending on the wind conditions and the system design.

  - **Cut - in Wind Speed** This is the minimum wind velocity below which no useful power output can be produced from wind turbine, typically between 3 and 4 m/s (10 and 14 km/h, 7 and 9 mph).

  - **Rated Wind Speed** (also associated with the **Nameplate Capacity**) This is the lowest wind velocity at which the turbine develops its full power. This corresponds to the maximum, safe electrical generating capacity which the associated electrical generator can handle, in other words the generator's rated electrical power output. The rated wind speed is typically about 15 m/s (54 km/h, 34 mph) which is about double the expected average speed of the wind. To keep the turbine operating with wind speeds above the rated wind speed, control systems may be used to vary the pitch of the turbine blades, reducing the rotation speed of the rotor and thus limiting the mechanical power applied to the generator so that the electrical output remains constant. Though the turbine works with winds speeds right up to the cut-out wind speed, its efficiency is automatically reduced at speeds above the rated speed so that it captures less of the available wind energy in order to protect the generator. While it would be possible to use larger generators to extract full power from the wind at speeds over the rated wind speed, this would not normally be economical because of the lower frequency of occurrence of wind speeds above the rated wind speed.
  - **Cut - out Wind Speed** This is the maximum safe working wind speed and the speed at which the wind turbine is designed to be shut down by applying brakes to prevent damage to the system. In addition to electrical or mechanical brakes, the turbine may be slowed down by stalling or furling.
    - **Stalling** This is a self correcting or passive strategy which can be used with fixed speed wind turbines. As the wind speed increases so does the wind angle of attack until it reaches its stalling angle at which point the "lift" force turning the blade is destroyed. However increasing the angle of attack also increases the effective cross section of the blade face-on to the

    wind, and thus the direct wind force and the associated stress on the blades. A fully stalled turbine blade, when stopped, has the flat side of the blade facing directly into the wind.

    - **Furling or Feathering** This is a technique derived from sailing in which the pitch control of the blades is used to decrease the angle of attack which in turn reduces the "lift" on the blades as well as the effective cross section of the aerofoil facing into the wind. A fully furled turbine blade, when stopped, has the edge of the blade facing into the wind reducing the wind force and stresses on the blade.

  The cut-out speed is specified to be as high possible consistent with safety requirements and practicality in order to capture as much as possible of the available wind energy over the full spectrum of expected wind speeds (See diagram of Wind Speed Distribution below). A cut-out speed of 25 m/s (90 km/h, 56 mph) is typical for very large turbines.

  - **Survival Wind Speed** This is the maximum wind speed that a given wind turbine is designed to withstand above which it can not survive. The survival speed of commercial wind turbines is in the range of 50 m/s (180 km/h, 112 mph) to 72 m/s (259 km/h, 161 mph). The most common survival speed is 60 m/s (216 km/h, 134 mph). The safe survival speed depends on local wind conditions is usually regulated by national safety standards.

- **Yaw Control**

  Windmills can only extract the maximum power from the available wind when the plane of rotation of the blades is perpendicular to the direction of the wind. To ensure this the rotor mount must be free to rotate on its vertical axis and the installation must include some form of yaw control to turn the rotor into the wind.

For small, lightweight installations this is normally accomplished by adding a tail fin behind the rotor in line with its axis. Any lateral component of the wind will tend to push the side of the tail fin causing the rotor mount to turn until the fin is in line with the wind. When the rotor is facing into the wind there will be no lateral force on the fin and the rotor will remain in position. Friction and inertia will tend to hold it in position so that it does not follow small disturbances.

Large turbine installations have automatic control systems with wind sensors to monitor the direction of the wind and a powered mechanism to drive the rotor into its optimum position.

- **Capacity Factor**

Electrical generating equipment is usually specified at its rated capacity. This is normally the maximum power or energy output which can be generated in optimal conditions. Since a wind turbine rarely works at its optimal capacity the actual energy output over a year will be much less than its rated capacity. Furthermore there will often be periods when the wind turbine can not deliver any power at all. These occur when there is insufficient wind to power the turbine system, or other periods, fortunately only a few, when the wind turbine must be shut down because the wind speed is dangerously high and exceeds the system cut-out speed.

The capacity factor is simply the wind turbine generator's actual energy output for a given period divided by the theoretical energy output if the machine had operated at its rated power output for the same period. Typical capacity factors for wind turbines range from 0.25 to 0.30. Thus a wind turbine rated at 1 MegaWatt will deliver on average only about

250 kiloWatts of power. (For comparison, the capacity factor of thermal power generation is between 0.70 and 0.90)

Wind Supply Characteristics

- **Wind speed**

Though the force and power of the wind are difficult to quantify, various scales and descriptions have been used to characterise its intensity. The Beaufort scale is one measure in common use. The lowest point or zero on the Beaufort scale corresponds to the calmest conditions when the wind speed is zero and smoke rises vertically. The highest point is defined as force 12 when the wind speed is greater than 34 metres per second (122 km/h, 76 mph). as occurs in tropical cyclones when the countryside is devastated by hurricane conditions.

Small wind turbines generally operate between force 3 and force 7 on the Beaufort scale with the rated capacity commonly being defined at force 6 with a wind speed of 12 m/s.

Below force 3 the wind turbine will not generate significant power.

At force 3, wind speeds range from 3.6 to 5.8 m/s (8 to 13 mph). Wind conditions are described as "light" and leaves are in movement and flags begin to extend.

At force 7, wind speeds range from 14 to 17 m/s (32 to 39 mph). Wind conditions are described as "strong" and whole trees are in motion.

With winds above force 7 small, domestic wind turbines should be shut down to prevent damage.

Large turbines used in the electricity grid are designed to work with wind speeds of up to 25 m/s (90 km/h, 56 mph) which corresponds to between force 9 (severe gale, 23 m/s) and force 10 (storm, 27 m/s) on the Beaufort Scale.

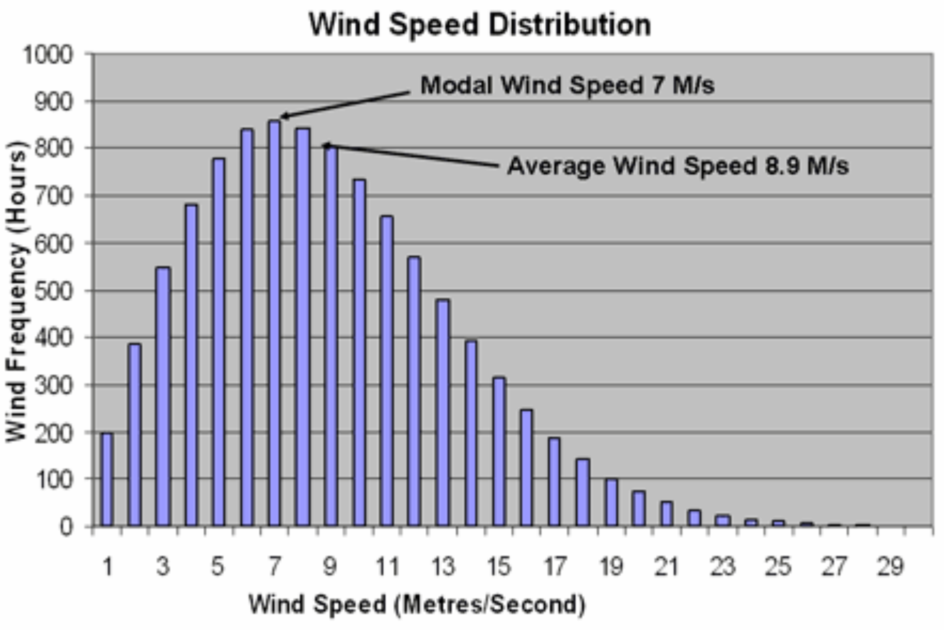
- **Wind Consistency**

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

- **Wind Speed Distribution**

  Care should be taken in calculating the amount of energy available from the wind as it is quite common to overestimate its potential. You can not simply take the *average* of the wind speeds throughout the year and use it to calculate the energy available from the wind because its speed is constantly changing and its power is proportional to the cube of the wind speed. (Energy = Power X Time). You have to weigh the probability of each wind speed with the corresponding amount of energy it carries.

  Experience shows that for a given height above ground, the frequency at which the wind blows with any particular speed follows a Rayleigh Distribution. An example is shown below.



Important Notes

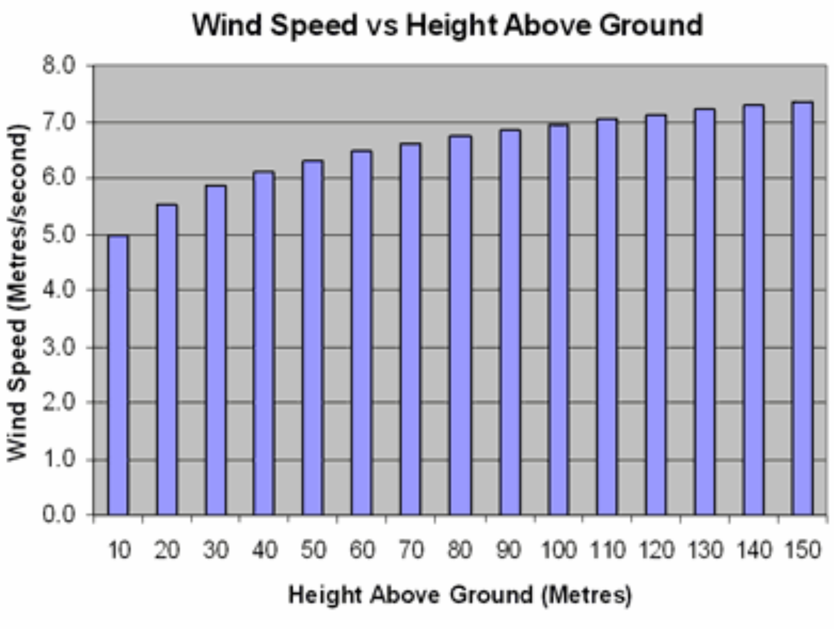
1. The modal wind speed, that is the speed at which the wind most frequently blows, is less than the average wind speed which is the speed often quoted as representing the typical wind conditions. For reference, the average wind speed across the UK quoted by the Department of Trade and Industry (DTI), is approximately 5.6 metres per second [m/s] at 10 metres above ground level (agl)."
2. Published average wind speeds are only reliable for open rural environments. Wind speeds just above roof level in urban environments will be considerably less than the quoted averages because of turbulence and shielding caused by buildings and trees. A wind turbine sited below the ridge of a building or at a similar height in the garden of an urban dwelling as often shown in the product sales literature is unlikely to provide the energy levels claimed in the specifications.
3. The distribution does not represent the energy content of the wind since this is proportional to the cube of the wind speed.
4. A distribution such as the one above is only valid for the prevailing

wind conditions at a particular height above the ground. Average wind speeds usually tend to increase with height then level off which is why wind turbines are usually installed as high above ground as possible.

An empirical formula developed by D.L. Elliott of Pacific Northwest Labs gives the wind speed **V** at a height **H** above ground level as

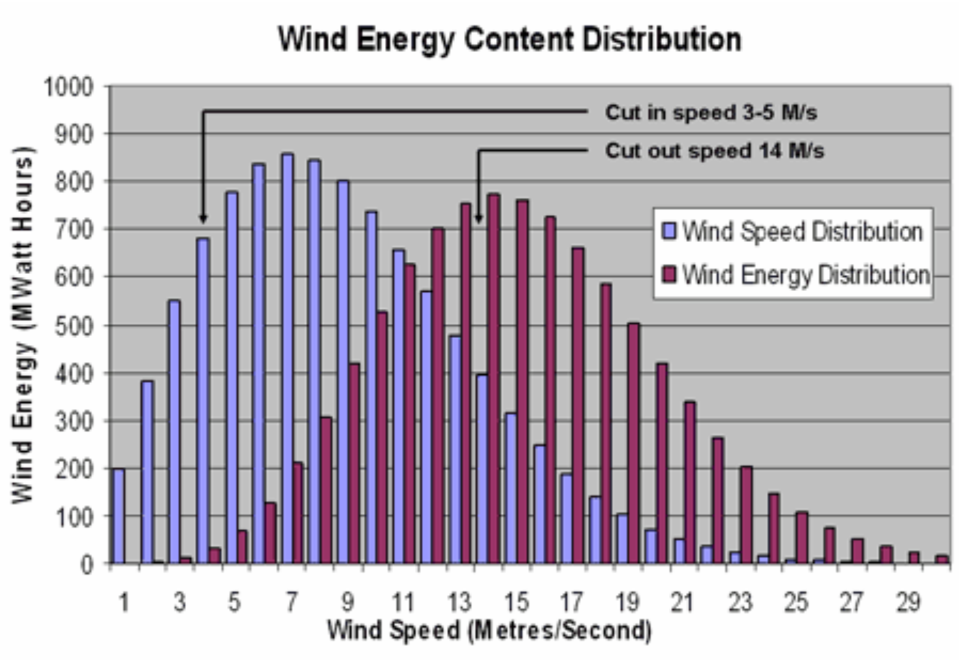
$$\mathbf{V = Vref\ (\ H\ /\ Href\ )^{\alpha}}$$

Where **Vref** is the reference wind speed at a reference height **Href** and the exponent **α** is a correction factor dependent on obstacles on the ground, the density of the air and wind stability factors. In wind resource assessments **α** is commonly assumed to be a constant 1/7th . The histogram below shows this relationship.



- **Wind Energy Distribution**

The histogram below shows the resulting distribution of the wind energy content superimposed on the Rayleigh wind speed distribution (above) which caused it. Unfortunately not all of this wind energy can be captured by conventional wind turbines.

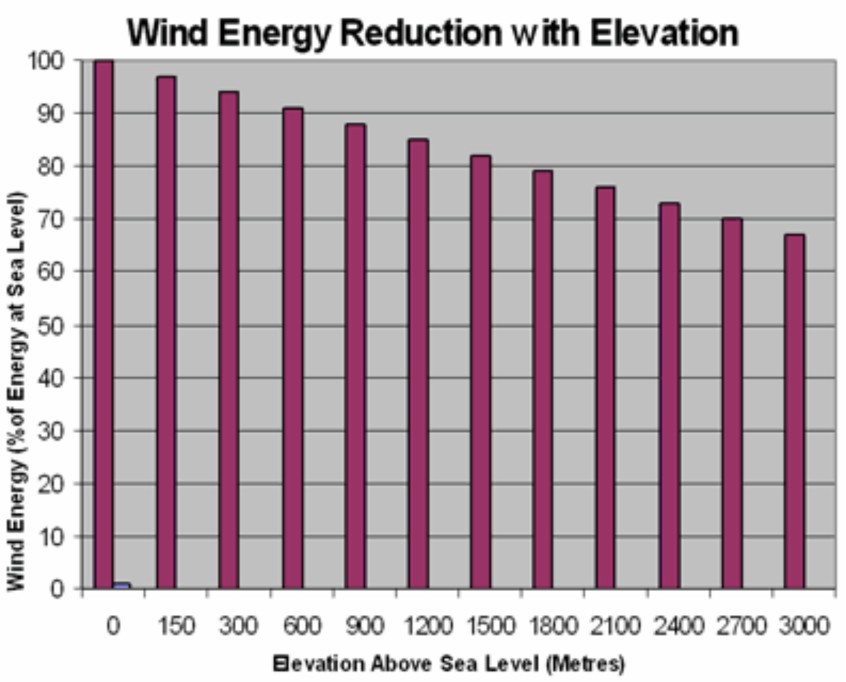


Notes

1. The peak wind energy occurs at wind speeds considerably above both the modal and average wind speeds since the wind energy content is proportional to the cube of its speed.
2. Very little energy is available at low speeds and most of this will be needed to overcome frictional losses in the wind turbine. Energy generation typically does not cut in until wind is blowing at speeds of at least 3 m/s to 5 m/s.
3. High wind speeds cause high rotation speeds and high stresses in the wind turbine which can can result in serious damage to the installation. To avoid these dangerous conditions, wind turbines are usually designed to cut out at wind speeds of around 25 m/s either by braking or feathering the rotor blades allowing the wind to spill over the blades, though smaller domestic installations may have lower operating limits.

4. Because of the limitations of the generating system and also upper speed limit at which the wind turbine can safely be used, it may capture only half or less of the available wind energy.

For a given wind speed the wind energy also depends on the elevation of the wind turbine above sea level. This is because the density of the air decreases with altitude and the wind energy is proportional to the air density. This effect is shown in the following histogram.



Notes

1. For a given wind speed the wind energy density decreases with increases in altitude. However at the same time the actual wind speeds tend to increase with height above ground level. Since the wind energy is proportional to the cube of the wind speed, the net effect is that wind energy tends to increase with the height above ground level.
2. As the density of air decreases with altitude, the wind energy density also decreases. By contrast the available solar energy

increases with altitude due to lower atmospheric absorption. See Solar Radiation and Insolation (Incident Solar Radiation).

- **Location Considerations**

  Generally marine locations and exposed hilltops provide the most favourable wind conditions with wind speeds consistently greater than 5 m/s.
  Turbulent conditions will reduce the amount of energy which can be extracted from the wind reducing in turn the overall efficiency of the system. This is more likely to be the case over land than over the sea. Raising the height of the turbine above the ground effectively lifts it above the worst of the turbulence and improves efficiency.

  Domestic wind turbines located between buildings in urban environments rarely operate at peak efficiency suffering from turbulence as well as being shielded from the wind by buildings and trees.

Practical Systems

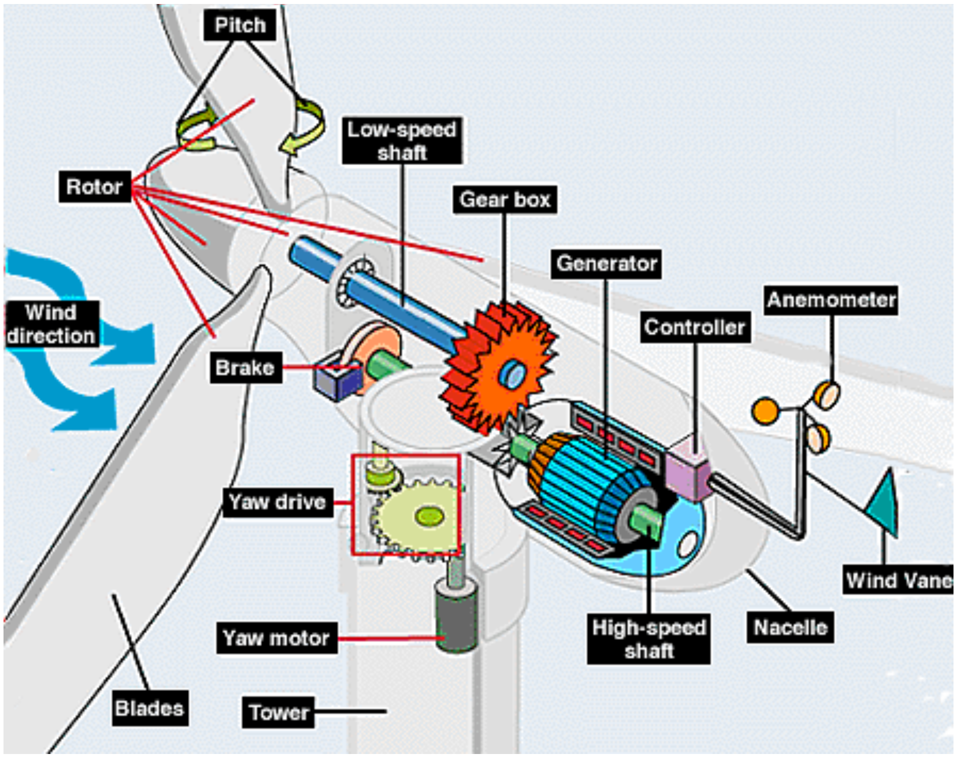
Community/Grid Installations

Vesta 7 MW Wind Turbines with a Rotor Diameters of 164 m

(Source The IET)

Grid connected systems are dimensioned for average wind speeds 5.5 m/s on land and 6.5 m/s offshore where wind turbulence is less and wind speeds are higher. While offshore plants benefit from higher sustainable wind speeds, their construction and maintenance costs are higher.

Large scale wind turbine generators with outputs of up to 8 MWe or more with rotor diameters up to164 metres are now functioning in many regions of the world with even larger designs in the pipeline.

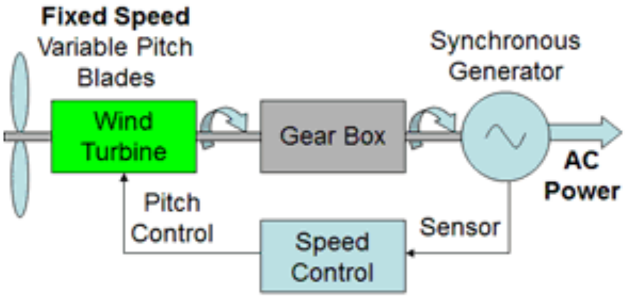


Source US DOE (EERE)

Large rotor blades are necessary to intercept the maximum air stream but these give rise to very high tip speeds. The tip speeds however must be limited, mainly because of unacceptable noise levels, resulting in very low rotation speeds which may be as low as 10 to 20 rpm for large wind turbines. The operating speed of the generator is however is much higher, typically 1200 rpm, determined by the number of its magnetic pole pairs and the frequency of the grid electrical supply. Consequently a gearbox must be used to increase the shaft speed to drive the generator at the fixed synchronous speed corresponding to the grid frequency.

Note that a **"synchronous generator"** is one whose electrical output frequency is synchronised to its shaft speed. It is not necessarily synchronised to the grid frequency, although that is usually an objective and extra, external controls are necessary to achieve this.

Fixed Speed Wind Turbine Generators



Large Scale Wind Power (Grid Systems)

A typical fixed speed system employs a rotor with three variable pitch blades which are controlled automatically to maintain a fixed rotation speed for any wind speed. The rotor drives a synchronous generator through a gear box and the whole assembly is housed in a nacelle on top of a substantial tower with massive foundations requiring hundreds of cubic metres of reinforced concrete.

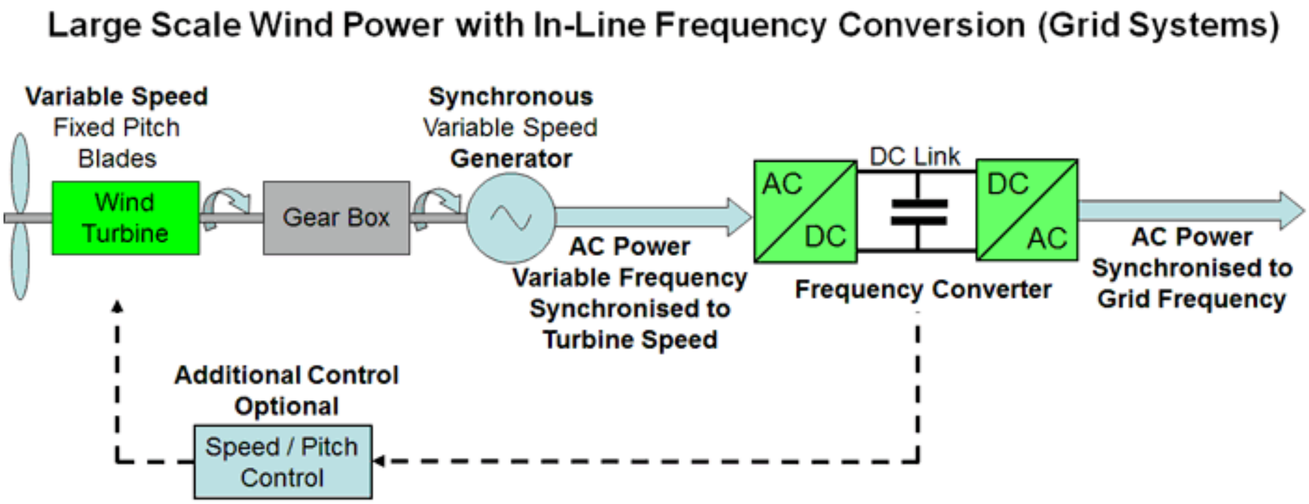
Fixed speed systems may however suffer excessive mechanical stresses. Because they are required to maintain a fixed speed regardless of the wind speed, there is no "give" in the mechanism to absorb gusty wind forces and this results in high torque, high stresses and excessive wear and tear on the gear box increasing maintenance costs and reducing service life. At the same time, the reaction time of these mechanical systems can be in the range of tens of milliseconds so that each time a burst of wind hits the turbine, a rapid fluctuation of electrical output power can be observed. Furthermore, variable speed wind turbines can capture 8-15% more of the wind's energy than constant speed machines. For these reasons, variable speed systems are preferred over fixed speed systems. See more about the properties of synchronous generators.

Variable Speed Wind Turbine Generators

A variable speed generator is better able to cope with stormy wind conditions because its rotor can speed up or slow down to absorb the forces when bursts of wind suddenly increase the torque on the system. The electronic control systems will keep the generator's output frequency constant during these fluctuating wind conditions.

- **Synchronous Generator with In-Line Frequency Control**

  Rather than controlling the turbine rotation speed to obtain a fixed frequency synchronised with the grid from a synchronous generator, the rotor and turbine can be run at a variable speed corresponding to the prevailing wind conditions. This will produce a varying frequency output from the generator synchronised with the drive shaft rotation speed. This output can then be rectified in the generator side of an AC-DC-AC converter and the converted back to AC in an inverter in grid side of the converter which is synchronised with the grid frequency. See following diagram. The grid side converter can also be used to provide reactive power (VArs) to the grid for power factor control and voltage regulation by varying the firing angle of the thyristor switching in the inverter and thus the phase of the output current with respect to the voltage. See an explanation and more details of why reactive power is needed in the section about Power Quality and Voltage Support as used in the utility grid.



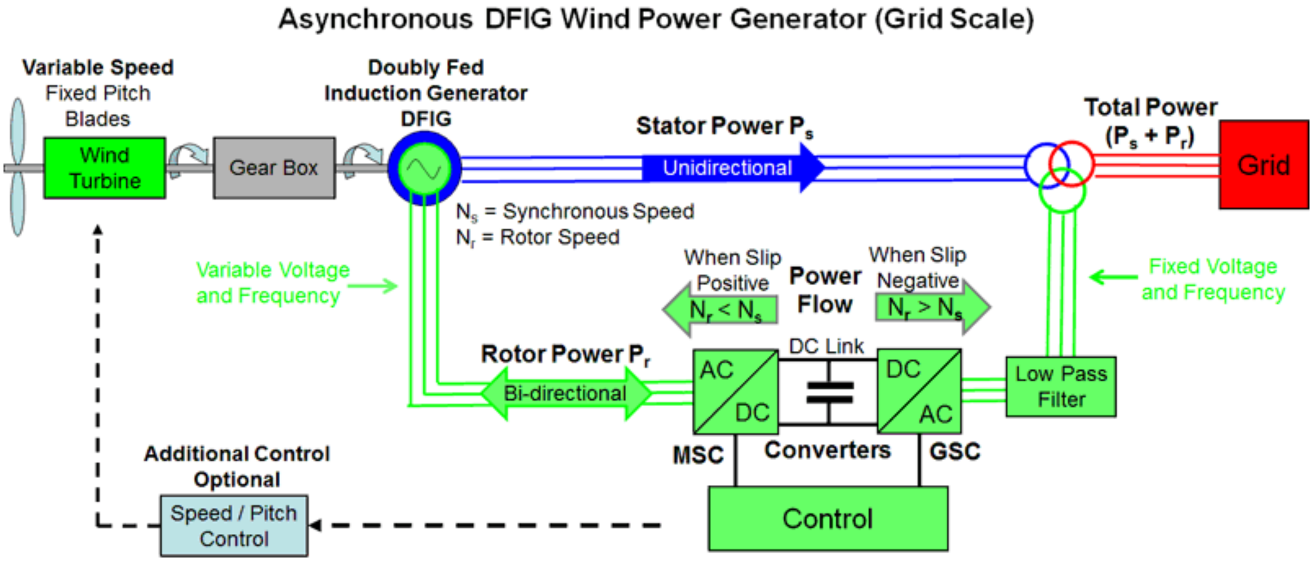
The range of wind speeds over which the system can be operated can be extended and mechanical safety controls can be incorporated by means of an optional speed control system based on pitch control of the rotor vanes as used in the fixed speed system described above.

One major drawback of this system is that the components and the electronic control circuits in the frequency converter must be dimensioned to carry the full generator power. The doubly fed induction generator DFIG overcomes this difficulty.

- **Doubly Fed Induction Generator - DFIG**

  DFIG technology is currently the preferred wind power generating technology. The basic grid connected asynchronous induction generator gets its excitation current from the grid through the stator windings and has limited control over its output voltage and frequency. The doubly fed induction generator permits a second excitation current input, through slip rings to a wound rotor permitting greater control over the generator output.

  The DFIG system consists of a 3 phase wound rotor generator with its stator windings fed from the grid and its rotor windings fed via a back to back converter system in a bidirectional feedback loop taking power either from the grid to the generator or from the generator to the grid. See the following diagram.



- ### Generator Operating Principle

The feedback control system monitors the stator output voltage and frequency and provides error signals if these are different from the grid standards. The frequency error is equal to the generator slip frequency and is equivalent to the difference between the synchronous speed and the actual shaft speed of the machine.

The excitation from the stator windings causes the generator to act in much the same way as a basic squirrel cage or wound rotor generator, (See more about the properties of induction generators and how they work.). Without the additional rotor excitation, the frequency of a slow running generator will be less than the grid frequency which provides its excitation and its slip would be positive. Conversely if it was running too fast the frequency would be too high and its slip would be negative.

The rotor absorbs power from the grid to speed up and delivers power to the grid in order to slow down. When the machine is running synchronously the frequency of the combined stator and rotor excitation matches the grid frequency, there is no slip and the machine will be synchronised with the grid.

- **Grid Side Converter - GSC :** Carries current at the grid frequency. It is an AC to DC converter circuit used to provide a regulated DC voltage to the inverter in the machine side converter (MSC). It is used maintain a constant DC link voltage. A capacitor is connected across the DC link between the two converters and acts as an energy storage unit. The grid side converter is used to maintain a constant DC link voltage. In the opposite direction the GSC invereter delivers power to the grid with the grid regulated frequency and voltage.

  As with the in-line converter described above, by adjusting the timing of the GSC inverter switching, the GSC converter also provides variable reactive power output to counterbalance the reactive power drawn from the grid enabling power factor correction as in the in-line frequency control system described above.

- **Machine Side Converter - MSC:** Carries current at slip frequency. It is an DC to AC inverter which is used to provide variable AC voltage and frequency to the rotor to control the torque and speed of the machine.

  When the generator is running too slowly, its frequency will be too low so that it is essentially motoring. The machine side converter takes DC power from the DC link and provides AC output power at the slip frequency to the rotor to eliminate its motoring slip and thus increase its speed. If the rotor is running too fast causing the generator frequency to be too high, the MSC extracts AC power from the rotor at the slip frequency causing it to slow down, reducing the generator slip, and converts the rotor output to DC passing it through the DC link to the GSC where it is converted to the fixed grid voltage and frequency and is inserted into the grid.

- **DFIG Control**
    - **Frequency**

The frequency of the rotor currents induced by transformer action from the stator is the same as the slip frequency and this is equivalent to the frequency error signal in the feedback loop.

The additional direct excitation of the rotor adds a second set of controlled currents to the currents already induced in the rotor by transformer action from the stator. These additional currents affect the rotation speed of the rotor in the same way as the stator induced currents, producing an additional driving torque on the rotor except that the additional rotor currents are independent of the speed of the rotor. The frequency of the control current supplied by the MSC can be precisely controlled to match and thus neutralise the slip frequency so that, with zero slip, the generator rotates at the synchronous frequency determined by the grid. The greater the slip, the greater the compensating frequency required.

The control system has to respond to both positive (motor) slip and negative (generator) slip.

To increase the speed of a slow running rotor, the phase sequence of the rotor windings is set so that the rotor magnetic field is in the same direction as the generator rotor producing negative slip to counteract and thus neutralise the rotor's positive slip. To reduce the rotor speed, the phase sequence of the rotor windings is set in opposite direction from the generator's rotation producing positive slip to counteract the rotor's negative slip.

When operating at synchronous speed the rotor current will be DC current and there will be no sip and no power flow through the rotor.

    - **Voltage**

      The generator output voltage is determined by the magnitude of the excitation current supplied to the rotor and this can be adjusted by means of the rotor input voltage provided by the MSC. A chopper or pulse width modulator PWM is used to generate the variable DC control voltage necessary. The converter feedback controls thus enable the excitation current to be regulated by the MSC to neutralise the voltage error signal and thus obtain a constant bus voltage matched to the grid voltage.

  - **DFIG Performance**
    - The DFIG system provides regulated power tied to the grid frequency and voltage when driven by varying levels of torque from the wind.
    - Typical speed control range is ± 30% of synchronous speed.
    - For a greater speed control range it may be necessary to implement separate pitch control on the wind turbine's rotor vanes.
    - The generator power flow is shared by the stator and the rotor with 70% or more coming from the stator. The feedback loop

only carries the slip power which is between 20% and 30% of the total.

- Because of the reduced power flowing through the converters, compared with the in-line control system described above above, they the DFIG converters can be implemented with less expensive lower power components.
- The DFIG machine can produce up to twice the power of a similar sized singly fed machine while incurring similar losses, however the losses in the electronic controls must be added to this. Nevertheless the DFIG machine efficiency is better that a singly fed machine.

Wind Farms

Grouping 10 to 100 wind turbines together in so called "wind farms" can lead to savings of 10% to 20% in construction, distribution and maintenance costs.

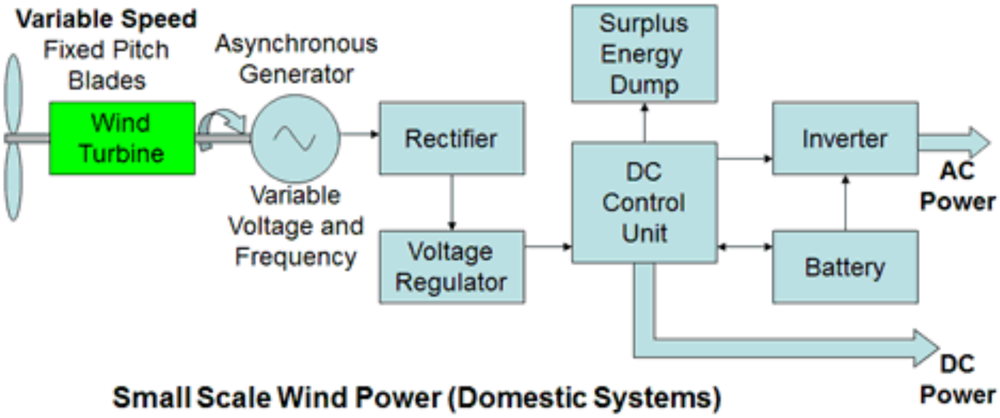
According to NREL the"footprint" of land needed to provide space for turbine towers, roads, and support structures is typically between 0.1 and 0.2 hectares (0.25 and 0.50 acres) per turbine. With the typical capacity of wind turbines installed in existing wind farms being around 2 MW, it would take a wind farm with 2000 wind turbines covering 200 to 400 hectares (500 to 1000 acres) just to replace the 4000 MWe power generated by the UK's Drax coal fired power station.

Unfortunately for the economics of wind turbines, the utility company needs to keep the equivalent capacity from other sources (conventional generating stations or batteries) just to keep the grid customers supplied when the wind is not blowing.

Domestic Wind Turbine Installations

1.6 kW Wind Turbine with 2.8 Metre Diameter Rotor by Cyclone Green Power Inc.

In a typical domestic system the wind turbine is coupled directly to a three phase asynchronous permanent magnet AC generator mounted on the same shaft. To save on capital costs, domestic installations do not have variable pitch rotor blades so the rotor speed varies with the wind speed. The generator output voltage and frequency are proportional to the rotor speed and the current is proportional to the torque on the shaft. The output is rectified and fed through a buck-boost regulator to an inverter which generates the required fixed amplitude and frequency AC voltage.



Small Scale Wind Power (Domestic Systems)

Note: There is possible confusion in the classification of the generator. It is actually a synchronous generator because the frequency of its output is directly synchronised with the rotor speed. In this application however it is called an asynchronous generator because the output frequency of the generator is not synchronised with the mains/utility frequency.

- **Urban Installations**

  Wind turbine blade sizes in urban applications are usually limited for practical reasons to less than about 1 metre (2 metres diameter) as well as by local planning ordinances and for similar reasons the height of the turbine above ground is limited to just above rooftop level but below treetop level.

  - **Economics**

    A typical domestic installation with a 1.75m swept diameter, (swept area of 2.4m^2), costs around £1500 ($2250). At the rated wind speed of 12.5m/s (28 mph) the wind power intercepted will be 2870 Watts, but after taking into account all the unavoidable system losses, the actual electrical output power will be around 1000 Watts. However this is at the upper end of the performance possibilities. Wind turbulence and shielding due to buildings and trees inhibits sustained strong, gust free wind flow and in any case, for most of the time, the wind speed will more likely be towards the lower end of the performance specification at 4 m/s (9 mph), that is a light breeze. At this speed the power output of the system will be about 32 Watts - Not enough to power a single light bulb. For much of the time the power generated could be less than the quiescent power drain of the inverter.

    Running with a constant power output of 32 Watts for a full year would generate only 280 kWh (280 Units) of electrical energy worth £28 at today's price of £0.10 ($0.15) per kWh. To put it into perspective, a typical UK household consumes about 5,000 kWh of electrical energy per year.

Because the system is connected directly to the grid there is no need for battery back-up and in any case the cost of the batteries would make an already weak economic case for the system even weaker. See also Grid Connected Systems

Thus small domestic rooftop wind turbine installations do not make a serious contribution to the household energy supply.

Self sufficiency and selling surplus energy back to the utility are out of the question and the payback period on the capital investment is out of sight.

  - **Carbon Footprints**

    As with solar power, if the investment fails the conventional economic tests, the notion of carbon footprints is often used to justify the expense, based on the potential for reducing the amount of greenhouse gases emitted by alternative methods of power generation.

- **Rural Installations**

  The economics of rural and remote locations make wind power more attractive than for urban locations. Because of the remoteness, connection to the electricity grid may be impossible or prohibitively expensive. Furthermore, larger, more efficient wind power installations are possible and the prevailing winds will also be higher. See also Stand

Alone Systems

- **Hybrid Installations**

  Hybrid systems combining wind and solar power provide energy diversity reducing the risk of power outages. Wind speeds are often high in the winter when the available solar energy is low and low in the summer when the available solar energy is high.

  Hybrid systems are discussed in more detail in the section on Remote Area Power Systems

Wind power provides a valuable complement to large scale base load power stations. Where there is an economic back-up, such as hydro power or large scale storage batteries, which can be called upon at very short notice, a significant proportion of electricity can be provided from wind.

See also Generators

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