Stationery Office; available at http://www.publications.parliament.uk/pa/cm200708/cmselect/cmdius/216/216ii.pdf (accessed 11 August 2011).

Salter, M. and Walker, C. (2010) *The Severn Barrage Digest*, report by two Members of Parliament, London, All Party Parliamentary Group on Angling; available at http://www.martinsalter.com/wp-content/uploads/2010/04/severn-barrage-digest-chapter-6-post-short-list-conclusions.pdf (accessed 11 August 2011).

SDC (2007) *Turning the Tide: Tidal Power in the UK*, Sustainable Development Commission; available at http://www.sd-commission.org.uk/publications/downloads/Tidal_Power_in_the_UK_Oct07.pdf (accessed 8 March 2011).

STPG (1986) *Tidal Power from the Severn*, Severn Tidal Power Group.

Twidell, J. W. and Weir, A. J. (2006) *Renewable Energy Resources* (2nd edition), Oxford, Taylor & Francis.

VerdErg (2009) *'SMEC' Spectral marine energy converter* [online], http://www.verderg.com/attachments/-01_SMEC_Doc_Oct%2009.pdf (accessed 8 March 2011).

WEC (2001) *2001 Survey of Energy Resources*, London, World Energy Council; available at http://www.worldenergy.org/documents/ser_sept2001.pdf (accessed 12 August 2011).

Westwood, A. (2005) *Refocus Marine Renewable Energy Report: Global Markets, Forecasts and Analysis 2005–2009*, London, Elsevier Science.

Chapter 7

Wind energy

By Derek Taylor

7.1 Introduction

Wind energy has been used for thousands of years for milling grain, pumping water and other mechanical power applications. Today, there are many thousands of windmills in operation around the world, a proportion of which are used for water pumping. But it is the use of wind energy as a pollution-free means of generating electricity on a significant scale that is attracting most current interest in the subject. Strictly speaking, a wind*mill* is used for milling grain, so modern technology for electricity generation is generally differentiated by use of the term **wind turbines**, partly because of their functional similarity to the steam and gas turbines that are used to generate electricity, and partly to distinguish them from their traditional forebears. Wind turbines are also sometimes referred to as **wind energy conversion systems (WECS)** and sometimes described as **wind generators** or **aerogenerators**.

Attempts to generate electricity from wind energy have been made (with various degrees of success) since the late nineteenth century when Professor James Blyth of the Royal College of Science and Technology, now Strathclyde University, built a range of wind energy devices to generate electricity, his first being in 1887. A later design built at Marykirk in Scotland continued to generate electricity for over 20 years.

For many years, small-scale wind turbines have been manufactured to provide electricity for remote houses, farms and remote communities, and for charging batteries on boats, caravans and holiday cabins (thousands of small turbines similar to that shown in Figure 7.1 are in use worldwide). More recently they have been used to provide electricity for cellular telephone masts and remote telephone boxes.

However, it is only since the 1980s that the technology has become sufficiently mature to enable rapid growth of the sector. Between the early 1980s and the late 2000s the cost of wind turbines fell steadily and the rated capacity of typical machines increased significantly. Now, on reasonably windy and accessible sites, wind turbines are one of the most cost-effective methods of electricity generation. Given continuing improvements in cost, capacity and reliability, it can be expected that wind energy will become even more economically competitive over the coming decades. Moreover, as wind turbines are increasingly deployed offshore, where wind speeds are generally higher and planning constraints perhaps less demanding, the technically accessible wind resource is massively increased. Of course, as will be seen later, there are significant additional technical challenges associated with offshore wind and the cost of generation is inevitably higher.

Figure 7.1 The 70 watt rated Marlec 'Rutland Wind Charger'

The improvements in wind power technology have made it one of the fastest growing renewable energy technologies worldwide in terms of installed rated capacity. A total of over 194 GW of wind generating capacity had been installed by the end of 2010, with almost 36 GW added in that year. This is about 11 times the capacity that had been installed by the end of 2000, and, at the time of writing, the current average growth rate is around 22% per annum.

To understand the machines and systems that extract energy from the wind involves an appreciation of many fields of knowledge, from meteorology, aerodynamics and planning to electrical, structural, civil and mechanical engineering. Hence, this chapter begins with a description of the atmospheric processes that give rise to wind energy. Wind turbines and their aerodynamics are then described, together with various ways of calculating their power and energy production. This is followed by discussions of the environmental impact and economics of wind energy, together with an examination of recent commercial developments and a discussion of its future potential. The final section looks at offshore wind power, which seems likely to be one of the most important areas of wind energy development in coming decades, especially for the UK and northern Europe.

7.2 The wind

As mentioned in Chapter 2, one square metre of the Earth's surface on or near the equator receives more solar radiation per year than one square metre at higher latitudes. The curvature of the Earth means that its surface becomes more oblique to the Sun's rays with increasing latitude. In addition, the Sun's rays have further to travel through the atmosphere as latitude increases, so more of the Sun's energy is absorbed *en route* before it reaches the surface. As a result of these effects, the tropics are considerably warmer than higher latitude regions.

This differential solar heating of the Earth's surface causes variations in atmospheric pressure, which in turn give rise to the movement of atmospheric air masses which are the principal cause of the Earth's wind systems (see Box 7.1 for more details).

BOX 7.1 The Earth's wind systems

Like all gases, air expands when heated, and contracts when cooled. Thus warm air is less dense than cold air and will rise to high altitudes when strongly heated by solar radiation.

A low pressure belt (with cloudy and rainy weather patterns) is created at the equator due to warm humid air rising in the atmosphere until it reaches the tropopause (the top of the troposphere). At the surface the equatorial region is called the 'doldrums' (from an old English word meaning dull) by early sailors who were fearful about becoming becalmed.

At the tropopause in the northern hemisphere the air moves northwards and in the southern Hemisphere it moves southwards. This air gradually cools until it reaches latitudes of about 30 degrees, where it sinks back to the surface, creating a belt of high pressure at these latitudes (with dry clear weather patterns). The majority of the world's deserts also occur in these high-pressure regions.

Some of the air that reaches the surface at these latitudes is forced back towards the low-pressure zone at the equator. These air movements are known as the '**trade winds**'. On reaching the equator these air movements complete the circulation of what is known as the **Hadley cell** – named after the scientist (George Hadley) who first described them in 1753.

However, not all of the air that sinks at the 30 degree latitudes moves toward the equator. Some of it moves poleward until it reaches the 60 degree latitudes, where it meets cold air coming from the poles at what are known as the 'polar fronts'. The interaction of the two bodies of air causes the warmer air to rise and most of this air cycles back to the 30-degree latitude regions where it sinks to the surface, contributing to the high-pressure belt. This completes the circulation of what is known as the **Ferrel cell** (named after William Ferrel who first identified it in 1856).

The remaining air that rises at the polar fronts moves poleward and sinks to the surface at the poles as it cools. It then returns to the 60-degree latitude region completing the circulation of what is known as the **polar Hadley cell** or **polar cell**.

There is a further complication in that, because the Earth itself rotates, winds moving across the Earth's surface are subject to a phenomenon known as the Coriolis Effect. The net result of this effect, given the Earth rotates in an eastwards direction, is that in the northern hemisphere 'north bound' winds are caused to veer 'right'. Such winds are known as 'westerlies' as, whilst they are veering toward an easterly direction, it is the convention when referring to wind direction to use the direction *from* which winds blow. In the southern hemisphere 'north bound' winds veer to the 'left' ('trade winds'). Likewise, 'south bound' winds veer 'right' ('trade winds') in the northern hemisphere and 'left' ('westerlies') in the southern hemisphere. Figure 7.2 shows the overall pattern of global wind circulation.

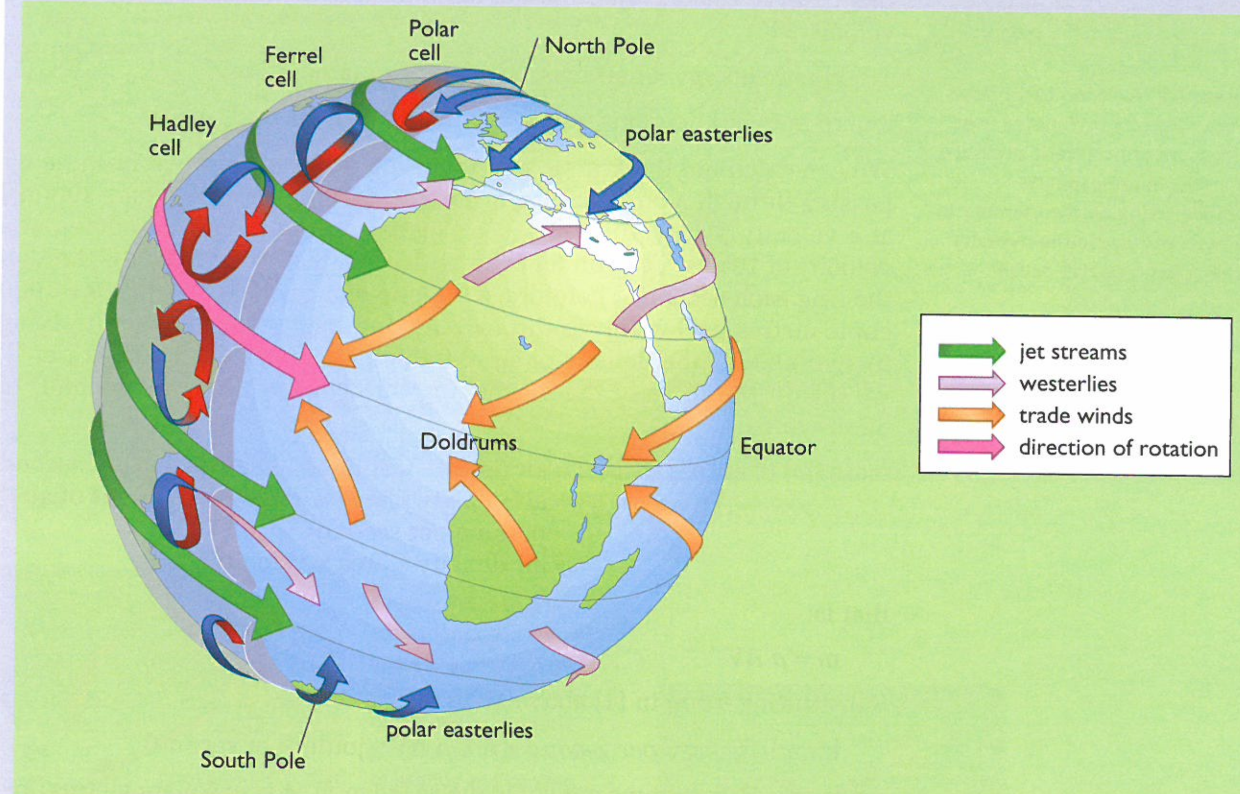


Figure 7.2 The global wind circulation (source: Burroughs et al., 1996)

Atmospheric pressure is the pressure resulting from the weight of the column of air above a specified surface area, with the unit of atmospheric pressure being known as the bar. Atmospheric pressure is measured by means of a barometer (Figure 7.3). These devices are usually calibrated in millibars (mbar), that is, thousandths of a bar. The average atmospheric pressure at sea level is about 1013.2 mbar (approximately 1 bar). The SI unit of pressure, the pascal (Pa), is defined as one newton per square metre and 1 bar is equivalent to 100 kPa.

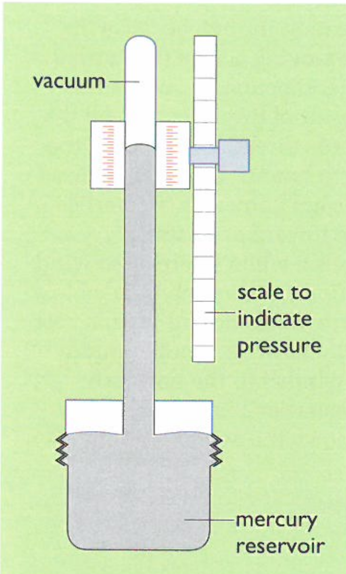


Figure 7.3 A Fortin barometer, an example of a barometer used to measure atmospheric pressure. Variations in atmospheric pressure acting on the mercury in the reservoir cause the mercury in the column to rise or fall

On the weather maps featured in television weather forecasts or in newspapers, there are regions marked 'high' and 'low', surrounded by contours (Figure 7.4). The regions marked 'high' and 'low' relate to the atmospheric pressure and the contours represent lines of equal pressure called **isobars**. The high-pressure regions tend to indicate fine weather with little wind, whereas the low-pressure regions tend to indicate changeable windy weather and precipitation.

In addition to the main global wind systems shown in Box 7.1 there are also local wind patterns, such as sea breezes (Figure 7.5) and mountain-valley winds (Figure 7.6).

Energy and power in the wind

The energy contained in the wind is its kinetic energy, and as we saw in Chapter 1 the kinetic energy of any particular moving mass (moving air in this case) is equal to half the mass, m, (of the air) times the square of its velocity, V:

$$\text{kinetic energy} = \text{half mass} \times \text{velocity squared} = \frac{1}{2}mV^2 \qquad (1)$$

where m is in kilograms and V is in metres per second (m s^{-1}).

We can calculate the kinetic energy in the wind if, first, we imagine air passing through a circular ring or hoop enclosing an area A (say 100 m^2) at a velocity V (say 10 m s^{-1}) (see Figure 7.7). As the air is moving at a velocity of 10 m s^{-1}, a cylinder of air with a length of 10 m will pass through the ring each second. Therefore, a volume of air equal to 100 × 10 = 1000 cubic metres (m^3) will pass through the ring each second. By multiplying this volume by the density of air, ρ (which at sea level is 1.2256 kg m^{-3}), we obtain the mass of the air moving through the ring each second. In other words:

mass (m) of air per second = air density × volume of air passing per second
= air density × area × length of cylinder of air passing per second
= air density × area × velocity

that is:

$$m = \rho AV$$

Substituting for m in (1) above gives:

kinetic energy *per second* = 0.5 ρAV^3 (joules per second)

where ρ is in kilograms per cubic metre (kg m^{-3}), A is in square metres (m^2) and V is in metres per second (m s^{-1}).

If we recall that energy per unit of time is equal to power, then the power in the wind is P (watts) = kinetic energy in the wind traversing the circular ring per second (joules per second), that is:

$$P = 0.5\,\rho AV^3 \qquad (2)$$

The main relationships that are apparent from the above calculations are that the power in the wind is proportional to:

- the density of the air
- the area through which the wind is passing (i.e. through a wind turbine rotor), and
- the cube of the wind velocity.

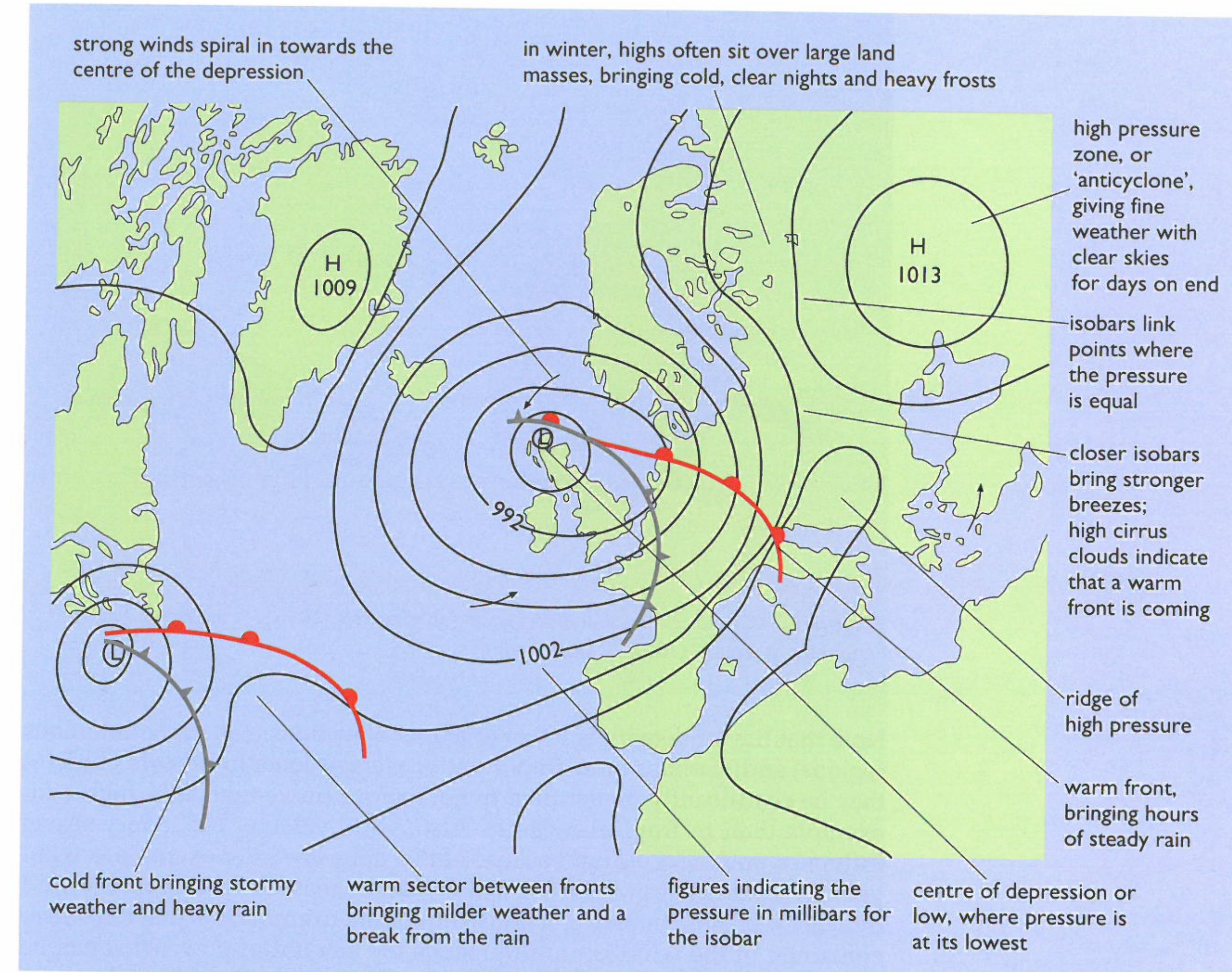


Figure 7.4 Typical weather map showing regions of high (H) and low (L) pressure

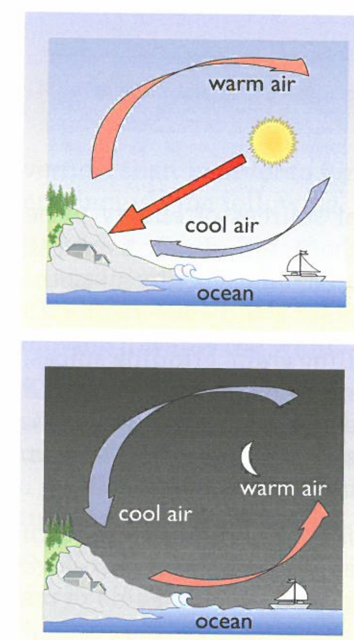


Figure 7.5 Sea breezes are generated in coastal areas as a result of the different heat capacities of sea and land, which give rise to different rates of heating and cooling. The land has a lower heat capacity than the sea and heats up quickly during the day, but at night it cools more quickly than the sea. During the day, the sea is therefore cooler than the land and this causes the cooler air to flow shoreward to replace the rising warm air on the land. During the night the direction of air flow is reversed

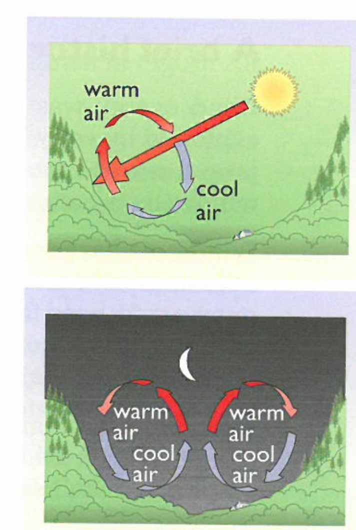


Figure 7.6 Mountain-valley winds are created when cool mountain air warms up in the morning and, as it becomes lighter, begins to rise: cool air from the valley below then moves up the slope to replace it. During the night the flow reverses, with cool mountain air sinking into the valley

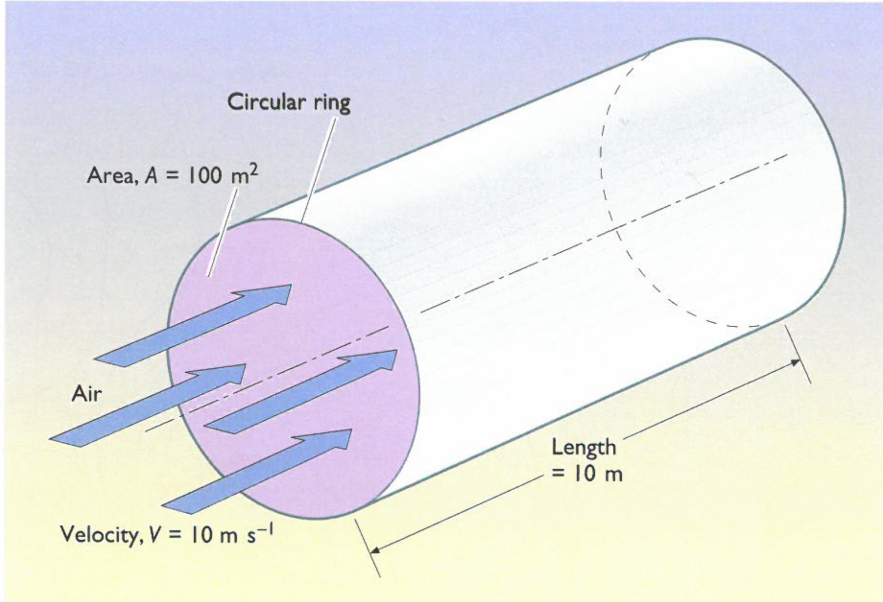


Figure 7.7 Cylindrical volume of air passing at velocity V (10 m s^{-1}) through a ring enclosing an area, A (100 m^2), each second

Note that the air density is lower at higher elevations (e.g. in mountainous regions) and, perhaps more importantly, average densities in cold climates may be significantly higher than in hot regions (more than 10% higher for example than in tropical regions). Also, wind velocity has a very strong influence on power output because of the 'cube law'. For example, a wind velocity increase from 6 m s^{-1} to 8 m s^{-1} will increase the power in the wind by a factor of more than two. It is also important to appreciate that the power contained in the wind is not in practice the amount of power that can be extracted by a wind turbine. This is because losses are incurred in the energy extraction/conversion process (see Section 7.4 on aerodynamics). Moreover there are additional mechanical-to-electrical power conversion losses.

7.3 Wind turbines

A brief history of wind energy

Wind energy was one of the first non-animal sources of energy to be exploited by early civilizations. It is thought that wind was first used to propel sailing boats, but the static exploitation of wind energy by means of windmills is believed to have been taking place for about 4000 years.

Windmills have traditionally been used for milling grain, grinding spices, dyes and paint stuffs, making paper and sawing wood. Traditional wind pumps were used for pumping water in Holland and East Anglia in the UK, and, because they often used identical forms of sails and support structures, they were (and are) often also referred to as windmills.

Many early windmills were of the *vertical-axis* type and, unlike modern wind turbines which are driven by lift forces (see below), these were drag-driven devices and relied on differences in drag on either side of the

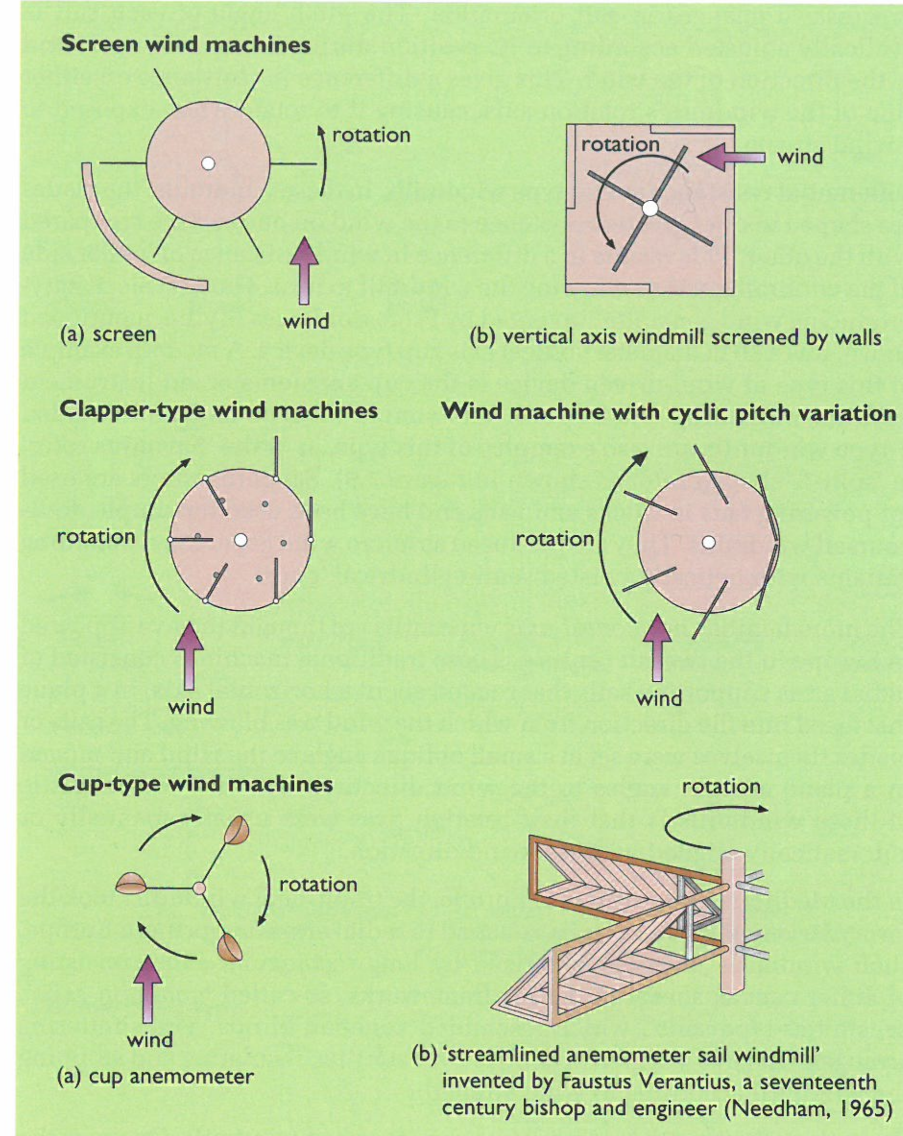


Figure 7.8 Some examples of traditional vertical-axis windmills

vertical shaft in order to function. Some examples are shown in Figure 7.8 and include the following.

Screened windmills. These windmills employ screens or partial walls around the windmill, which are positioned to screen the windmill sails from the wind during the 'backward' part of the cycle, when the sails are moving towards the wind.

'Clapper' windmills. These windmills are so called because the moveable sails 'clap' against stops as the rotor turns with the wind (forwards), maximizing their air resistance, but align themselves with the wind (like a weather vane) when on the part of their cycle in which they are moving into the wind (backwards), so reducing their air resistance.

Cyclically pivoting sail windmills. These windmills are similar to the 'clapper' windmills, but use a more complex mechanism to achieve progressive changes in sail orientation. The pitch angle of each sail is cyclically adjusted according to its position during its rotation cycle and to the direction of the wind. This gives a difference in resistance on either side of the windmill's rotation axis, causing it to rotate when exposed to a wind stream.

Differential resistance or cup type windmills. In these windmills, the blades are shaped to offer greater resistance to the wind on one surface compared with the other. This results in a difference in wind resistance on either side of the windmill axis, so allowing the windmill to turn. The first electricity-producing wind generator, invented by Professor James Blythe, mentioned above, was a 10 m diameter vertical axis cup type device. A modern example of this type of wind-driven device is the cup anemometer, an instrument used for measuring wind speed. The simple 'S' type and multi-bladed S-type windmills are also examples of this type, as is the 'Savonius rotor' (a 'split-S' shaped rotor as shown in Figure 7.9). Savonius rotors are used for powering fans in trucks and vans and have been used for simple do-it-yourself windmills. They are produced as micro wind generators, including variants with helically twisted semi-cylindrical 'cups'.

The more familiar *horizontal-axis* windmills are thought to have appeared in Europe in the twelfth century. These traditional machines consisted of radial arms supporting sails that rotated about a horizontal axis, in a plane that faced into the direction from which the wind was blowing. The sails or blades themselves were set at a small oblique angle to the wind and moved in a plane at right angles to the wind direction. Another characteristic of these windmills is that their rotation axes were usually manually or automatically aligned with the wind direction.

In the Mediterranean regions of Europe, the traditional windmills took the form of triangular canvas sails attached to radial arms. In northern Europe, such windmills were characterized by long rectangular sails consisting of either canvas sheets on lattice frameworks, so-called 'common sails', or 'shutter-type sails', which resembled venetian blinds. The shuttering arrangement gave a degree of control over starting, regulating and stopping the windmill according to wind strength.

In northern Europe there were two main forms of windmill. One was the less common 'post mill', in which the whole windmill was moved about a large upright post when the wind direction changed; the other was the more common 'tower mill' (Figure 7.10), in which the rotor and cap were supported by a relatively tall tower, usually of masonry. In the tower mill, only the cap (in combination with the rotor and its shaft) were moved in response to changes in wind direction. The sails turned fairly slowly and provided mechanical power.

At their zenith, before the Industrial Revolution, it is estimated that there were some 10 000 of these windmills in Britain (Golding, 1955) and they formed a familiar feature of the countryside.

Wind turbine types

The variety of machines that has been devised or proposed to harness wind energy is considerable and includes many unusual devices. Figure 7.9 shows a small selection of the various types of machines that have been proposed over the years.

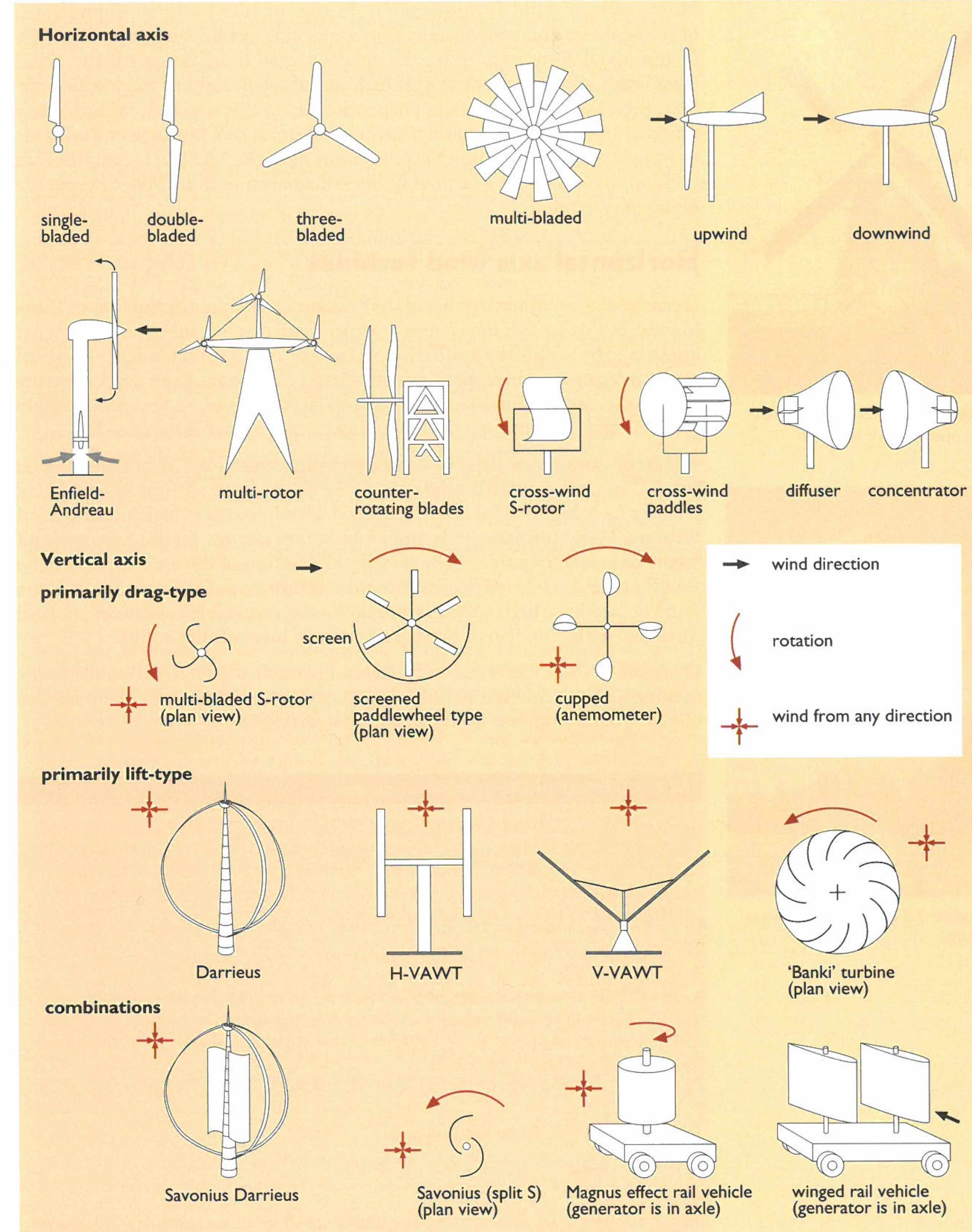


Figure 7.9 Some examples of the machines that have been proposed for wind energy conversion. (Source: partly based on Eldridge, 1975. For further information on these machines see Eldridge, 1975 and Golding, 1955). The figure is divided into two sections, Horizontal axis and Vertical axis machines.

Figure 7.10 Traditional north European tower windmill

Figure 7.11 Multi-bladed wind pump

Most modern wind turbines come in one of two basic configurations: horizontal axis and vertical axis. Horizontal axis turbines are predominantly of the 'axial flow' type (i.e., the rotation axis is in line with the wind direction), whereas vertical axis turbines are generally of the 'cross flow' type (i.e., the rotation axis is perpendicular to the wind direction). They range in size from very small machines that produce a few tens or hundreds of watts to very large turbines producing as much as 7.5 MW. Larger turbines rated at 10 to 15 MW are now being considered and 20 MW designs are being investigated.

Horizontal axis wind turbines

Horizontal axis wind turbines (HAWTs) generally have either two or three blades, but can have many more. Multi-bladed wind turbines have what appears to be virtually a solid disc covered by many solid blades (usually of slightly cambered sheet metal construction). They have been used since the nineteenth century for water pumping on farms (Figure 7.11). Appropriately for their application they produce high torque at low rotor speeds.

The term '**solidity**' is used to describe the fraction of the swept area that is solid. Wind turbines with large numbers of blades, such as these multi-bladed devices, have highly solid swept areas and are referred to as **high-solidity** wind turbines. Wind turbines with small numbers of narrow blades have a swept area that is largely void: only a very small fraction of the area appears to be 'solid' – such devices are referred to as **low-solidity** wind turbines. Multi-blade wind pumps have **high-solidity rotors** and modern electricity-generating wind turbines (with one, two or three blades) have **low-solidity rotors**.

Low-solidity devices work effectively at much higher rotational speeds making them attractive for electricity generation (Box 7.2 discusses the effect of blade number on turbine characteristics).

BOX 7.2 Effect of the number of blades

The speed of rotation of a wind turbine is usually measured in either revolutions per minute (rpm) or radians per second (rad s^{-1}). The **rotation speed** in revolutions per minute (rpm) is usually symbolized by N and the **angular velocity** in radians per second is usually symbolized by Ω. The relationship between the two is given by:

$$1 \text{ rpm} = \frac{2\pi}{60} \text{ rad s}^{-1} = 0.10472 \text{ rad s}^{-1}$$

A useful alternative measure of wind turbine rotor speed is **tip speed**, U, which is the **tangential velocity** of the rotor at the tip of the blades, measured in metres per second. It is the product of the **angular velocity**, Ω, of the rotor and the **tip radius**, R (in metres):

$$U = \Omega R$$

Alternatively, U can be defined as:

$$U = \frac{2\pi RN}{60}$$

By dividing the **tip speed**, U, by the **undisturbed wind velocity**, V_0, upstream of the rotor, we obtain a non-dimensional ratio known as the **tip speed ratio**, usually symbolized by λ. This ratio provides a useful measure against which aerodynamic efficiency can be plotted. The aerodynamic efficiency of a wind

turbine is usually described as its **power coefficient** (effectively the ratio of power output from the turbine to the theoretical power in the wind). This quantity is symbolized by C_P and given as a fraction, such that 1 equates to 100% efficiency. When the power coefficient is plotted against tip speed ratio, such $C_P - \lambda$ curves provide an effective way to present the performance of a rotor and to compare wind turbines with differing characteristics.

A wind turbine of a particular design can operate over a range of tip speed ratios, but will usually operate with its best (maximum) efficiency at a particular tip speed ratio, i.e. when the velocity of its blade tips is a particular multiple of the wind velocity. This optimum tip speed ratio (λ_{opt}) is also commonly denoted as λ_{max} with the corresponding efficiency (i.e. power coefficient) being C_{Pmax}. The optimum tip speed ratio for a given wind turbine rotor will depend upon both the number of blades and the width of each blade.

In order to extract energy as efficiently as possible, the blades have to interact with as much as possible of the wind passing through the rotor's **swept area**. The blades of a high-solidity, multi-blade wind turbine interact with all the wind at very low tip speed ratios, whereas the blades of a low-solidity turbine have to travel much faster to 'virtually fill up' the swept area, in order to interact with all the wind passing through. If the tip speed ratio is too low, some of the wind travels through the rotor swept area without interacting with the blades; whereas if the tip speed ratio is too high, the turbine offers too much resistance to the wind, so that some of the wind goes around it. A two-bladed wind turbine rotor with each blade the same width as those of a three-bladed rotor will have an optimum tip speed ratio *one-third higher* than that of a three-bladed rotor. Optimum tip speed ratios for modern low-solidity wind turbines range between about 6 and 20.

In theory, the more blades a wind turbine rotor has, the more efficient it is. However, when there are large numbers of blades in a rotor, the flow becomes more disturbed, so that they aerodynamically interfere with each other. Thus high-solidity wind turbines tend to be less efficient overall than low-solidity turbines. Of low-solidity machines, three-bladed rotors tend to be the most energy efficient; two-bladed rotors are slightly less efficient and one-bladed rotors slightly less efficient still. Wind turbines with more blades can be generally expected to generate less aerodynamic noise as they operate at lower tip speeds (see Section 7.6) than wind turbines with fewer blades.

The mechanical power that a wind turbine extracts from the wind is the product of its angular velocity and the torque imparted by the wind. **Torque** is the moment about the centre of rotation due to the driving force imparted by the wind to the rotor blades. Torque is usually measured in newton metres (N m) (see Box 7.4). For a given amount of power, the *lower* the angular velocity the *higher* the torque; and conversely, the *higher* the angular velocity the *lower* the torque.

The pumps that are used with water pumping wind turbines require a high starting torque to function. Multi-bladed turbines are therefore generally used here because of their low tip speed ratios and resulting high torque characteristics.

Conventional electrical generators run at speeds many times greater than most wind turbine rotors so they generally require some form of gearing when used with wind turbines. Low-solidity wind turbines are better suited to electricity generation because they operate at high tip speed ratios and therefore do not require as high a gear ratio to match the speed of the rotor to that of the generator. In addition, many low-solidity small wind turbines (and even certain very large wind turbines) have avoided using gearboxes by using directly coupled low-speed multi-pole generators.

Figure 7.12 Two-bladed HAWT (WEG MS400 turbine)

Figure 7.13 Three-bladed HAWT (Vestas V52 850 kW turbine)

Figure 7.14 Single bladed HAWT (MBB 600 kW turbine)

Modern *low-solidity* HAWT rotors evolved from traditional windmills and superficially resemble aircraft propellers. Wind turbines with such rotors are by far the most common design manufactured today. They have a clean streamlined appearance, due in part to their design being driven by aerodynamic considerations derived largely from developments in aircraft wing and propeller design. HAWT rotors generally have two or three wing-like blades (Figures 7.12 and 7.13). They are almost universally employed to generate electricity. Some experimental single-bladed HAWTs have also been produced (Figure 7.14) and continue to be researched.

Vertical axis wind turbine

Vertical axis wind turbines (VAWTs), unlike their horizontal axis counterparts, can harness winds from any direction without the need to reposition the rotor when the wind direction changes. However, despite this advantage, they have found little commercial success to date, in part due to issues with power quality, cyclic loads on the tower systems and the lower efficiency of some VAWT designs. A technical description of how VAWTs operate is given in Section 7.4.

The modern VAWT evolved from the ideas of the French engineer, Georges Darrieus, whose name is used to describe one of the VAWTs that he invented in 1925 – such devices were independently re-invented in Canada by South and Rangi at the National Aeronautical Establishment of the National Research Council in the 1960s (South and Rangi, 1972). This device, which resembles a large eggbeater, has curved blades (each with a symmetrical aerofoil cross-section) the ends of which are attached to the top and bottom of a vertical shaft (see Figure 7.15). Several hundred were manufactured in the USA and installed in wind farms in California in the 1980s. A small number were produced in Canada, including 'Eole', the largest VAWT yet built, a 100 m tall 60 m diameter turbine. Eole operated for six years from 1988 in Quebec and achieved a 94% availability (see Figure 7.15(b)).

These Darrieus VAWTs were guyed structures, which added complexity and limited their height, but a new design of Darrieus VAWT, mounted on a free-standing cantilevered tower that avoids the difficulties of guys, is under development in New Mexico (VPM, 2011). There is also a floating enhanced Darrieus VAWT design under development (FWC, 2011).

The blades of a Darrieus VAWT take the form of a 'troposkien' (the curved, arch-like shape taken by a spinning skipping rope). This shape is a structurally efficient one, well suited to coping with the relatively high centrifugal forces acting on VAWT blades. However, they can be difficult to manufacture, transport and install, though the advent of modern composites and manufacturing methods may help to address some of the difficulties. In order to overcome these problems, straight-bladed VAWTs have been developed: these include the 'H'-type vertical axis wind turbine (H-VAWT) and the 'V'-type vertical axis wind turbine (V-VAWT).

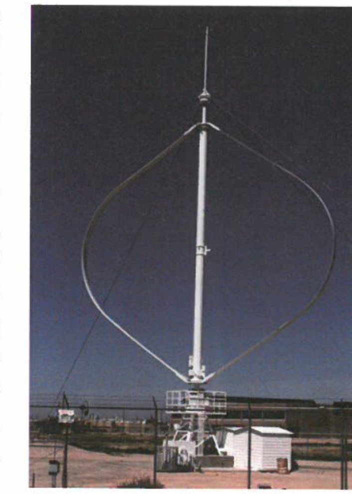
The H-VAWT (Figure 7.16) consists of a tower (which may house a vertical shaft), capped by a hub to which is attached two or more horizontal cross arms that support the straight, upright, aerofoil blades. In the UK, this type of turbine was developed by VAWT Ltd which built 125 kW and 500 kW prototypes at Carmarthen Bay and a 100 kW turbine on the Isles of Scilly in the 1980s. There continues to be interest in H-VAWTs both at small scale and for large offshore applications, (VertAx, 2011).

The V-VAWT consists of straight aerofoil blades attached at one end to a hub on a vertical shaft and inclined in the form of a letter 'V'. Its main features include a shorter tower, ground/water level-mounted generator options, ground/water level blade installation and the ability to self start without needing complex variable pitch blades or the electrical starting required by other types of VAWTs. Experimental prototypes were tested at the Open University (Figure 7.17(a)) as was the *Sycamore Rotor*, a single bladed version. New generation *V2 Turbine* variants (Figure 7.17(b)) suited to large scale and offshore fixed/floating applications are being researched by the author.

At the present time, VAWTs are not generally economically competitive with HAWTs. However, they continue to attract research as they should, in principle, offer significant advantages over HAWTs in terms of blade loading and fatigue, if they can be built in very large sizes (such as are becoming desired for offshore applications). Whilst VAWTs are subject to wind-induced cyclic loads (which do not progressively increase with increasing size of turbine) they are not subject to the major gravitational cyclic loadings (which do progressively increase with rotor diameter) that large diameter HAWTs experience. As the Canadian Eole demonstrated in the 1980s/90s, large VAWTs can be operated with very high reliability.

More recent variants in vertical axis wind turbines are VAWTs with helically shaped blades. These were first advocated in the 1990s by the Swedish engineer Olle Ljungstrom and additionally by US engineer Alexander Gorlov. Gorlov also suggested such turbines could be used in hydro and, as discussed in Chapter 6, tidal current applications (Gorlov, 1998). Stimulated by perceived concerns about cyclic torque (due to the cyclic variation in the position of a VAWTs blade, relative to the wind direction – see Section 7.4), in the 1990s Ljungstrom produced designs of Darrieus VAWTs that employed helically shaped blades. A number of more recent designs have employed such blades. In practice, however, simply employing three blades should usually be sufficient to even out the torque variation for VAWTs, without the extra complexity and cost of manufacturing helical blades (Musgrove, 1990).

As was mentioned above, most types of VAWT (with aerofoil blades) are not able to self-start without some extra mechanism (as they are generally unable to produce sufficient aerodynamic starting torque). Examples of such additions are drag-driven 'vertical axis starter rotors' (which can reduce aerodynamic efficiency), complex variable pitch blades, or some form of electrical starting mechanism. Electrically assisted starting is not a major issue for the medium/large scale VAWTs employed in wind farms, but it is a major shortcoming for small/micro scale VAWTs, especially for off-grid applications or on relatively low wind speed sites, when electrically started VAWTs can consume large amounts of electricity, thus greatly reducing their net productivity (Day et al., 2010).

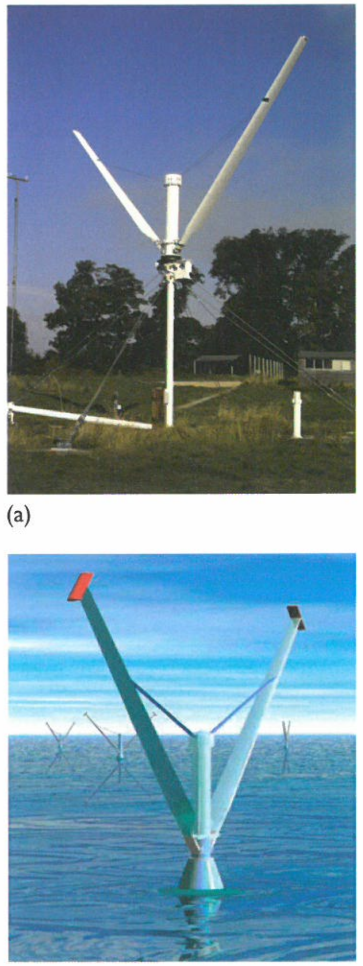


(a)

(b)

Figure 7.15 (a) Seventeen metre diameter Darrieus-type VAWT at Sandia National Laboratories, New Mexico. (b) Sixty metre diameter Eole VAWT in Quebec, Canada

Figure 7.16 500 kW 'H'-type VAWT at Carmarthen Bay, Wales



(a)

(b)

Figure 7.17 (a) V-VAWT prototype developed and tested at the Open University in Milton Keynes in the 1980s (b) Multi-megawatt scale V-Turbine concept in offshore configuration

7.4 Aerodynamics of wind turbines

Aerodynamic forces

When a force is transferred by a moving solid object to another solid object, the second object will generally move in either the same direction or in a direction at a small angle (less than 90 degrees) to the direction of motion of the first object, unless subjected to another force. However, the method by which forces are transferred from a fluid to a solid object is very different.

Wind turbines are operating in an unconstrained fluid, in this case air. To understand how they work, two terms from the field of aerodynamics will be introduced. These are 'drag' and 'lift'.

An object in an air stream experiences a force that is imparted from the air stream to that object (Figure 7.18). We can consider this force to be equivalent to two component forces acting in perpendicular directions, known as the *drag* force and the *lift* force. The magnitude of these drag and lift forces depends on the shape of the object, its orientation to the direction of the air stream, and the velocity of the air stream.

The **drag force** is the component that is in line with the direction of the air stream. A flat plate in an air stream, for example, experiences maximum drag forces when the direction of the air flow is perpendicular (that is, at right angles) to the flat side of the plate; when the direction of the air stream is in line with the flat side of the plate, the drag forces are at a minimum. Traditional vertical axis windmills and undershot water wheels (see Chapter 5) are driven largely by drag forces.

Objects designed to minimize the drag forces experienced in an air stream are described as streamlined, because the lines of flow around them follow smooth, stream-like lines. Examples of streamlined shapes are teardrops, the shapes of fish such as sharks and trout, and aeroplane wing sections (aerofoils) (Figure 7.19).

The **lift force** is the component that is at right angles to the direction of the air stream. It is termed 'lift' force because it is the force that enables aeroplanes to *lift* off the ground and fly, though in other applications it may induce a *sideward* (as in a sailboat) or *downward* force (as in the downforce aerofoil used in some racing cars). Lift forces acting on a flat plate are smallest when the direction of the air stream is at a zero angle to the flat surface of the plate. At small angles relative to the direction of the air stream – that is, when the so-called *angle of attack* (see below for more detail) is small – a low pressure region is created on the 'downstream' (or 'leeward') side of the plate as a result of an increase in the air velocity on that side (Figures 7.20 and 7.21 show this effect on aerofoil sections).

In this situation, there is a direct relationship between air speed and pressure: the faster the airflow, the lower the pressure (i.e. the greater the 'suction effect'). This phenomenon is known as the **Bernoulli effect** after Daniel Bernoulli, the Swiss mathematician who first explained it. The lift force thus acts as a 'suction' or 'pulling' force on the object, in a direction at right angles to the airflow.

As well as enabling aeroplanes and gliders to fly, it is the lift force that propels modern sailing yachts, and supports and propels helicopters. Lift is also the principal force that drives a modern wind turbine rotor and thus allows it to produce power.

Aerofoils

Arching or cambering a flat plate will cause it to induce higher lift forces for a given angle of attack, but the use of so-called **aerofoil sections** is even more effective. There are two main types of aerofoil section that are conventionally distinguished: asymmetrical and symmetrical (Figure 7.22). Both have a markedly convex upper surface, a rounded end called the 'leading edge' (which faces the direction from which the air stream is coming), and a pointed or sharp end called the 'trailing edge'. It is the shape of the 'under surface' or high pressure side of the sections that identifies the type. Asymmetrical aerofoils are optimized to produce most lift when the underside of the aerofoil is closest to the direction from which the air is flowing. Symmetrical aerofoils are able to induce lift equally well (although in opposite directions) when the air flow is approaching from either side of the **chord line** (the 'length', from the tip of its leading edge to the tip of its trailing edge, of an aerofoil section).

The angle which an aerofoil (or flat or cambered plate profile) makes with the direction of an airflow, measured against a reference line (usually

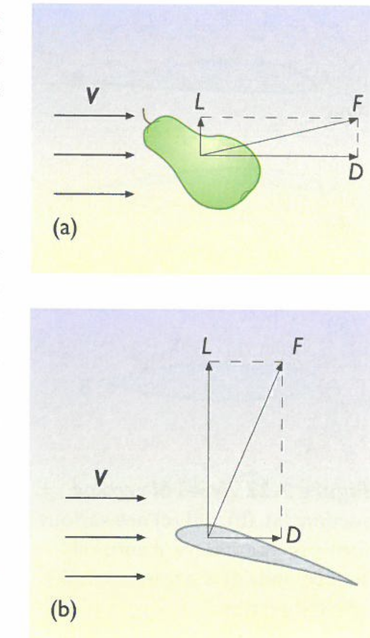


Figure 7.18 (a) and (b) An object in an air stream is subjected to a force, *F*, from the air stream. This is composed of two component forces: the drag force, *D*, acting in line with the direction of air flow and the lift force, *L*, acting at 90° to the direction of air flow

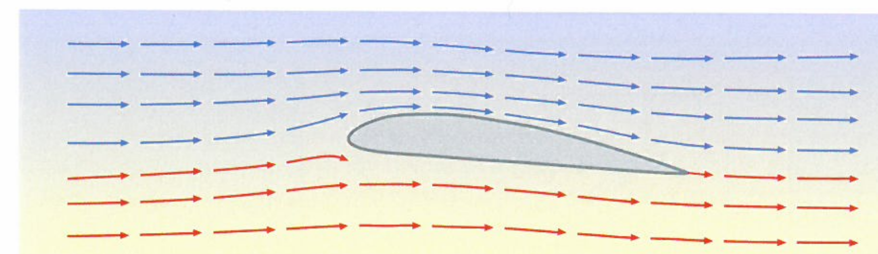


Figure 7.20 Streamlined flow around an aerofoil section

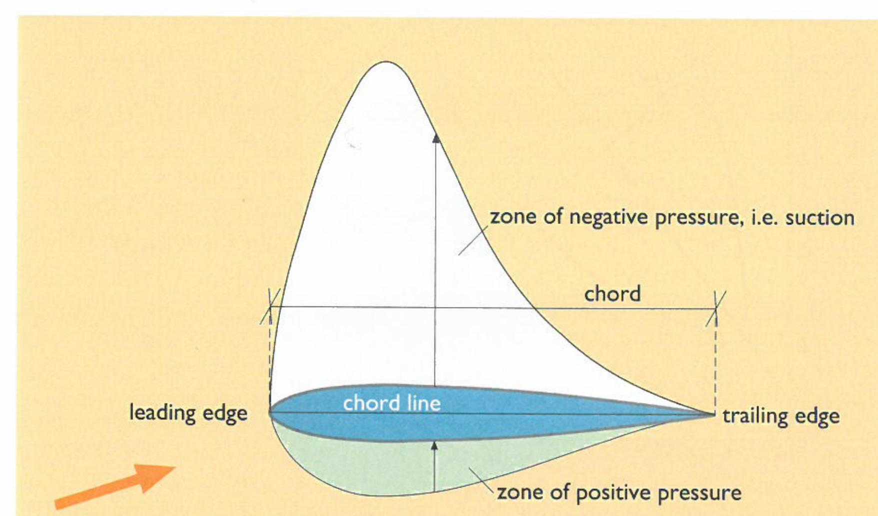


Figure 7.21 Zones of low and high pressure around an aerofoil section in an air stream

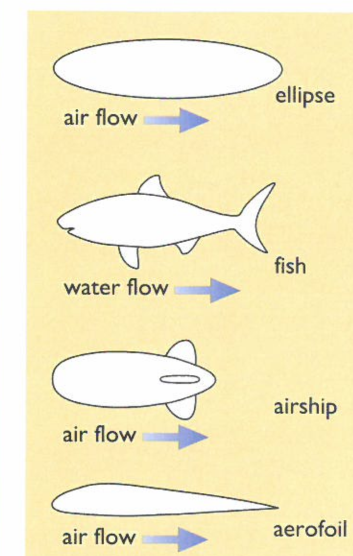


Figure 7.19 Some examples of streamlined shapes

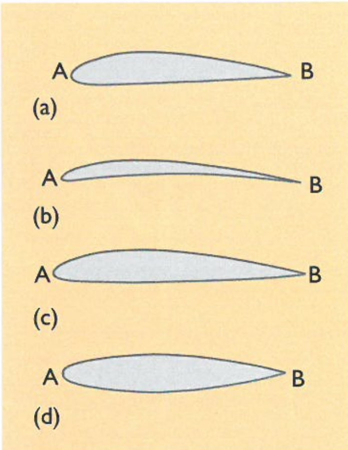


Figure 7.22 Types of aerofoil section: (a), (b) and (c) are various forms of asymmetrical aerofoil section and (d) is a symmetrical aerofoil section

the chord line of the aerofoil), is called the **angle of attack** α *(alpha)* (Figure 7.23). When airflow is directed towards the underside of the aerofoil, the angle of attack is usually referred to as positive.

When employed as a wing profile, asymmetrical aerofoil sections will, subject to a net incident airflow velocity (in aircraft this is due to forward flight), tend to accelerate the airflow over the more convex 'upper' surface. The high air speed thus induced results in a large reduction in pressure over the upper surface relative to the lower surface. This results in a 'suction' effect which 'lifts' the aerofoil-shaped wing, although it should be noted that this lift can only be sustained if the airflow leaves the aerofoil at the downstream edge (known as the trailing edge) in a smooth manner that prevents the high pressure air recirculating around the trailing edge and cancelling out the reduced pressure. The strength of the lift force induced by an aerofoil section is well demonstrated by its ability to support the entire mass of a large aircraft such as the Airbus A380.

The lift and drag characteristics of many different aerofoil shapes, for a range of angles of attack, have been determined by measurements taken in wind tunnel tests, and catalogued (e.g. in Abbott and von Doenhoff, 1958). The lift and drag characteristics measured at each angle of attack can be described using non-dimensional **lift** and **drag coefficients** (C_L and C_D) or as **lift to drag ratios** (C_L/C_D). These are defined in Box 7.3.

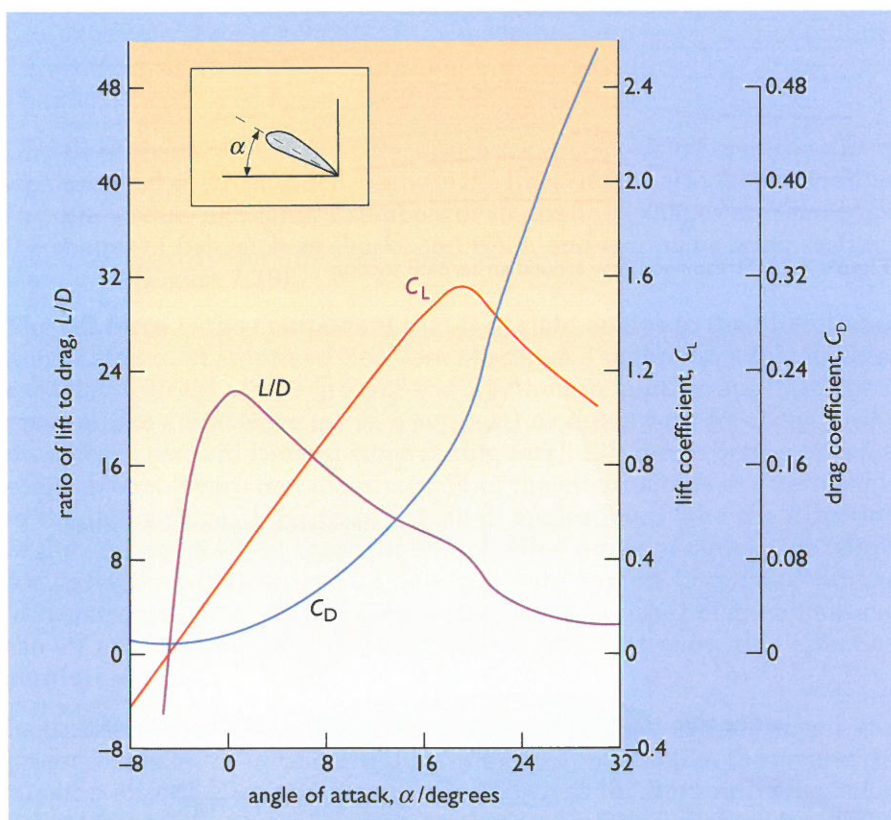


Figure 7.23 Lift coefficient, C_L, drag coefficient, C_D, and lift to drag ratio (*L*/*D*) versus angle of attack, α (shown inset), for a Clark Y aerofoil section. The region just to the right of the peak in the C_L curve corresponds to the angle of attack at which stall occurs

BOX 7.3 Aerofoil sections and lift and drag coefficients

Note that the chord of an aerofoil section is also the same as the *width* of the blade in a wind turbine at a given position along the blade.

Drag coefficient (C_D)

The drag coefficient of an aerofoil is given by the following expression:

$$C_D = \frac{D}{0.5\rho V^2 A_b}$$

where:

D is the drag force in newtons (N)

ρ is the air density in kilograms per cubic metre (kg m^{-3})

V is the velocity of the air approaching the aerofoil in metres per second (m s^{-1})

A_b is the blade area (i.e. chord × length) in square metres (m^2).

In the case of a blade element, the area is equal to the mean chord × length of the blade element.

Lift coefficient (C_L)

The lift coefficient of an aerofoil is given by the following expression:

$$C_L = \frac{L}{0.5\rho V^2 A_b}$$

where L is the lift force in newtons.

The lift and drag coefficients of an aerofoil can be measured in a wind tunnel at different angles of attack and wind velocities. The results of such measurements can be presented in either tabular or graphical form as in Figure 7.23.

Each aerofoil has an angle of attack at which the lift to drag ratio (C_L/C_D) is at a maximum. This angle of attack results in the maximum force and is thus the most efficient setting of the blades of a HAWT. Consequently, plots of this ratio against angle of attack can be useful to turbine designers (Figure 7.23).

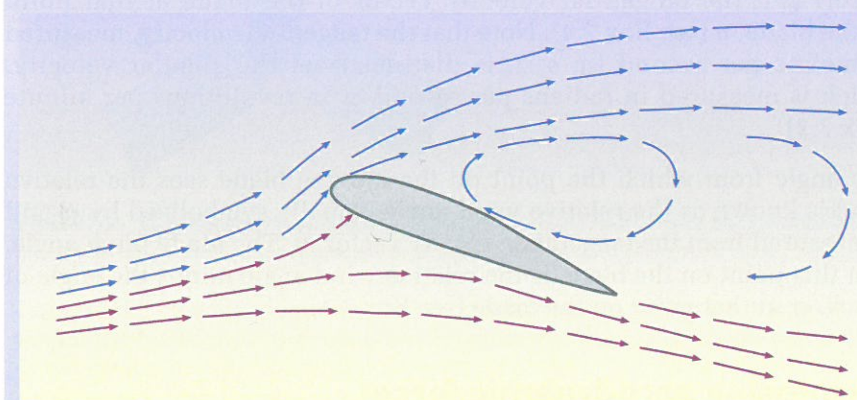


Figure 7.24 Aerofoil section in stall

Another important characteristic relationship of an aerofoil is its **stall angle**. This is the angle of attack at which the aerofoil exhibits stall behaviour. Stall occurs when the flow suddenly leaves the suction side of the aerofoil (when the angle of attack becomes too large), resulting in a dramatic loss in lift and an increase in drag (Figures 7.23 and 7.24). When this happens during the flight of an aeroplane, it can be extremely dangerous unless the pilot can make the plane recover. One of the methods used by wind turbines to limit the power extracted by the rotor in high winds takes advantage of this phenomenon; such turbines are known as stall regulated (see below for more details).

undisturbed wind velocity is reduced by one-third, in other words, when the axial interference factor, a, is equal to one-third. The value of 59.3% is often referred to as the **Betz limit**.

The relative wind angle, ϕ, is the angle that the relative wind makes with the blade (at a particular point with local radius, r, along the blade) and is measured from the plane of rotation. (Note: if it were not for the fact that the wind is slowed down as a result of the wind turbine extracting energy – in other words if V_0 was not reduced to V_1 at the rotor – the tip speed ratio would be equal to the reciprocal of the tangent of the relative wind angle at the blade.) The angle of attack, α, at this point on the blade can be measured against the relative wind angle, ϕ. The blade pitch angle (usually represented by β) is then *equal* to the relative wind angle *minus* the angle of attack. Since the rotor is constrained to rotate in a plane at right angles to the undisturbed wind, the driving force at a given point on the blade is that component of the aerofoil lift force that *acts in the plane of rotation*. This is given by the product of the lift force, L, and the sine of the relative wind angle, ϕ (that is, $L \sin \phi$). The component of the drag force in the rotor plane at this point is the product of the drag force, D, and the cosine of the relative wind angle, ϕ (that is, $D \cos \phi$).

The torque, q (that is, the moment about the centre of rotation of the rotor in the plane of the rotor), in newton metres (N m) at this point on the blade is equal to the *product* of the *net driving force in the plane of rotation* (that is, the component of lift force in the plane of rotation *minus* the component of the drag force in the rotor plane) and the local radius, r. The total torque, Q, acting on the rotor can be calculated by summing the torque at all points along the length of the blade and multiplying by the *number* of blades. The power from the rotor is the *product* of the total torque, Q and the rotor's angular velocity, Ω.

Why are rotor blades twisted?

The magnitude and direction of the relative wind angle, ϕ, varies along the length of the blade according to the local radius, r. Equation (3) shows that the tangential velocity varies with radius, so as the tangential speed *decreases* towards the hub, the relative wind angle, ϕ, *progressively increases* (see Figure 7.26). A HAWT rotor designed for optimum performance will have a tapered blade, and to have a constant angle of attack along its length (assuming the same aerofoil section is used throughout its length), it will have to have a built-in twist. The amount of twist will vary (as the relative wind angle varies) progressively from tip to root. Figure 7.26 demonstrates the progressive twist of such a HAWT rotor blade. Most manufacturers of HAWT blades use tapered and twisted blades, although it is possible to build functional HAWT rotor blades that are not twisted. These are cheaper, but less efficient and how well they function depends in part on both the aerofoil characteristics and the overall blade pitch angle.

Blade pitch

As well as the blade pitch angle defined above the term **blade pitch** also refers to the whole blade's angular position about the blade's longitudinal axis (also known as the pitch axis) such that in the case of a **variable pitch** rotor blade, the whole blade is able to be rotated about its pitch axis. In most cases all of the blades of a variable pitch HAWT rotor change pitch at the same time in order to:

- optimise the turbine's power production across a range of wind speeds (in order to maintain the angle of attack at or near to the optimal angle across a range of wind speeds)
- reduce its output at high wind speeds
- to stop the rotor during very high wind speeds or to 'park' the rotor (such that the blade pitch is in its 'feathered' position, e.g. each blade pitch is at or near 90 degrees, relative to the plane of rotation), when it is necessary to prevent the rotor from operating for any reason.

In the case of a **fixed pitch** rotor the blade pitch angle remains unchanged, which makes them less productive and less controllable. Most large wind turbines employ variable pitch blades, but most micro wind turbines and small wind turbines and some medium-scale wind turbines use fixed pitch blades.

Stall control of wind turbines

Let us assume that a wind turbine is rotating at a constant rotation speed, regardless of wind speed, and that the blade pitch angle is fixed. As the wind speed *increases* the tip speed ratio *decreases*. At the same time, the relative wind angle *increases*, causing an increase in the angle of attack.

It is possible to take advantage of this characteristic to control a turbine in high winds, if the rotor blades are designed so that above the rated wind speed they become less efficient because the angle of attack approaches the stall angle. This results in a loss of lift, and thus torque, on the regions of the blade that are in 'stall'.

This method of so-called **stall regulation** has been employed successfully on numerous fixed-pitch HAWT rotors and has also been employed on most modern lift-driven VAWT rotors. However, as turbines have increased in size this approach to power

regulation has generally been discontinued in HAWTs in favour of variable speed turbines with variable pitch regulation. The main reasons for this are that it is very hard for designers to predict exactly when a given rotor will stall and that variable pitch rotors are more efficient over a range of wind speeds.

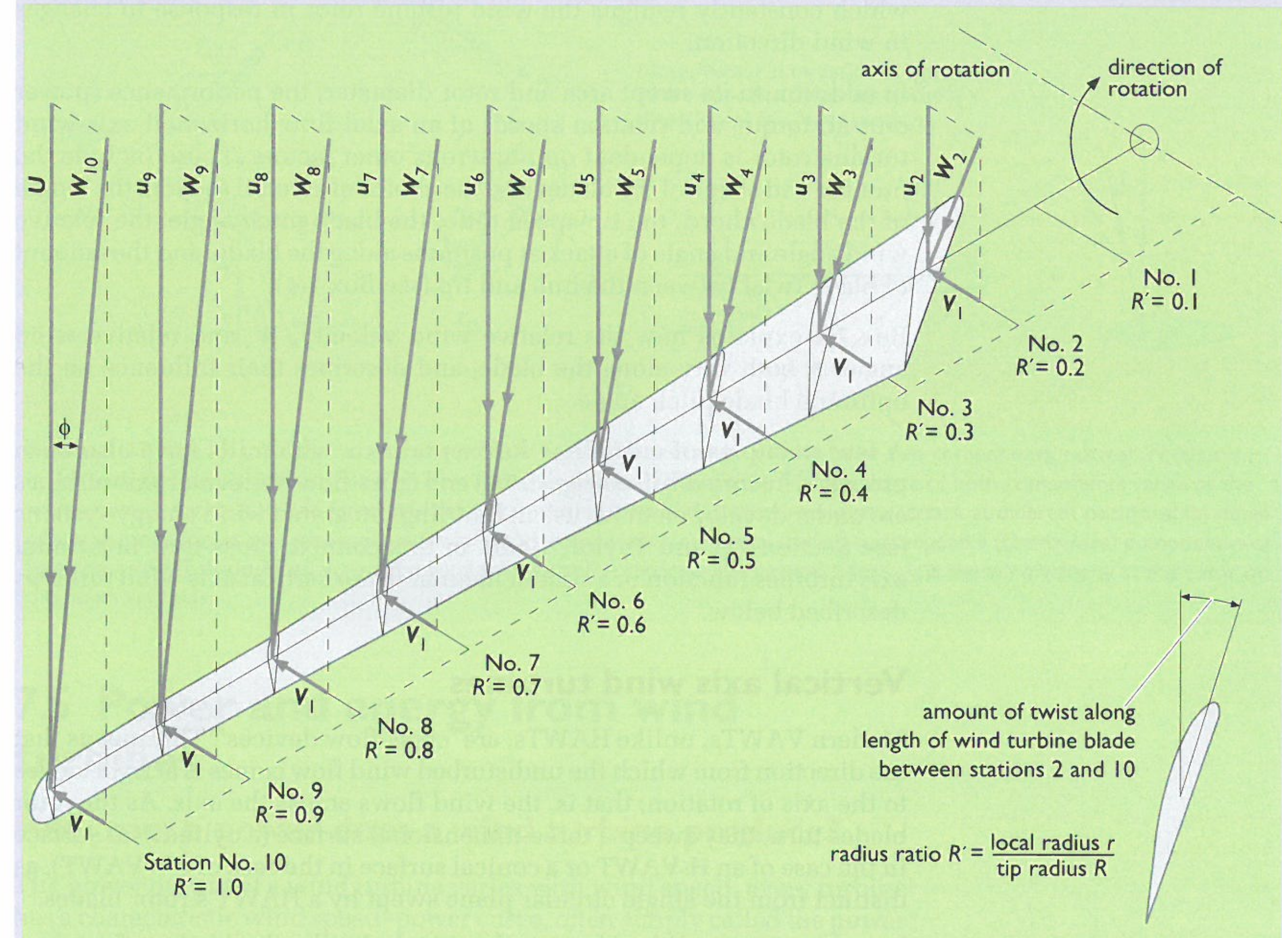


Figure 7.26 Three-dimensional view of an optimally tapered and twisted HAWT rotor blade design (the blade is shown in a horizontal position and moving through the upward part of its cycle about its axis of rotation). The figure shows how the relative wind angle, ϕ, changes along the blade span (length). Note that the blade aerofoil section and the angle of attack are assumed to be constant along the length of the blade. The diagram (lower right) of the view along the blade indicating the amount of built-in twist along the length of the blade shows the blade cross-section at station 2: the cross section of the blade at station 10 has been omitted for clarity

By contrast, in a VAWT with fixed pitch blades, under the same conditions, the angle of attack at a given position on the rotor blade is *constantly varying throughout its rotation cycle*.

During the normal operation of a horizontal axis rotor, the direction from which the aerofoil 'sees' the wind is such that the angle of attack remains positive throughout.

In the case of a vertical axis rotor, however, the angle of attack changes from positive to negative and back again over each rotation cycle. This means that the 'suction' side reverses during each cycle, so a symmetrical aerofoil has to be employed to ensure that power can be produced irrespective of whether the angle of attack is positive or negative.

Horizontal axis wind turbines

Most horizontal axis wind turbines are axial flow devices – the rotation axis is maintained in line with wind direction by a 'yawing' mechanism, which constantly realigns the wind turbine rotor in response to changes in wind direction.

In addition to its swept area and rotor diameter, the performance (power output, torque and rotation speed) of an axial flow horizontal axis wind turbine rotor is dependent on numerous other factors. These include the number and shape of the blades and the choice of aerofoil section, the length of the blade chord, the tip speed ratio, the blade pitch angle, the relative wind angle and angle of attack at positions along the blade, and the amount of blade twist between the hub and tip (see Box 7.4).

Box 7.4 explains how the relative wind velocity, $\boldsymbol{W}$, and relative wind angle, ϕ, both vary along the blade, and describes their influence on the optimum blade pitch angle.

A few examples of cross-flow horizontal axis windmills have also been proposed historically (see Figure 7.9) and cross-flow horizontal axis turbines are under development for use in building integrated wind energy systems (see Section 7.8 and Taylor, 1998). In this context, cross-flow horizontal axis turbines function in a similar manner to the vertical axis wind turbines described below.

Vertical axis wind turbines

Modern VAWTs, unlike HAWTs, are 'cross-flow devices'. This means that the direction from which the undisturbed wind flow comes is at right angles to the axis of rotation; that is, the wind flows across the axis. As the rotor blades turn, they sweep a three-dimensional surface (a cylindrical surface in the case of an H-VAWT or a conical surface in the case of a V-VAWT), as distinct from the single circular plane swept by a HAWT's rotor blades.

In contrast to traditional vertical-axis windmills, the blades of modern vertical axis wind turbines extract most of the power from the wind as they pass across the front and rear – as distinct from one side (relative to the undisturbed wind direction) of the swept surface.

A vertical axis wind turbine will function with the wind blowing from any compass direction, but let us assume initially that it is blowing from one particular direction and also that the setting angle of the blade is such that its chord is in line with a tangent to the circular path of rotation (that is, it has 'zero set pitch'). Clearly, the angle of the blade, in relation to the direction of the undisturbed wind, changes from zero to 360 degrees over each cycle of rotation. It might appear that the angle of attack of the wind to the blade would vary by the same amount, and so it might seem impossible for a VAWT to operate at all. However, we have to take into account the fact that when the blade is moving, the relative wind angle 'seen' by the blade is the resultant ($\boldsymbol{W}$) of the wind velocity V_1 at the rotor and the blade velocity $\boldsymbol{u}$ (see Box 7.4). Provided that the blade is moving sufficiently fast relative to the wind velocity (in practice, this means at a tip speed ratio of three or more), the angle of attack that the blade makes with the relative wind velocity $\boldsymbol{W}$ will only vary within a small range (see Figure 7.27).

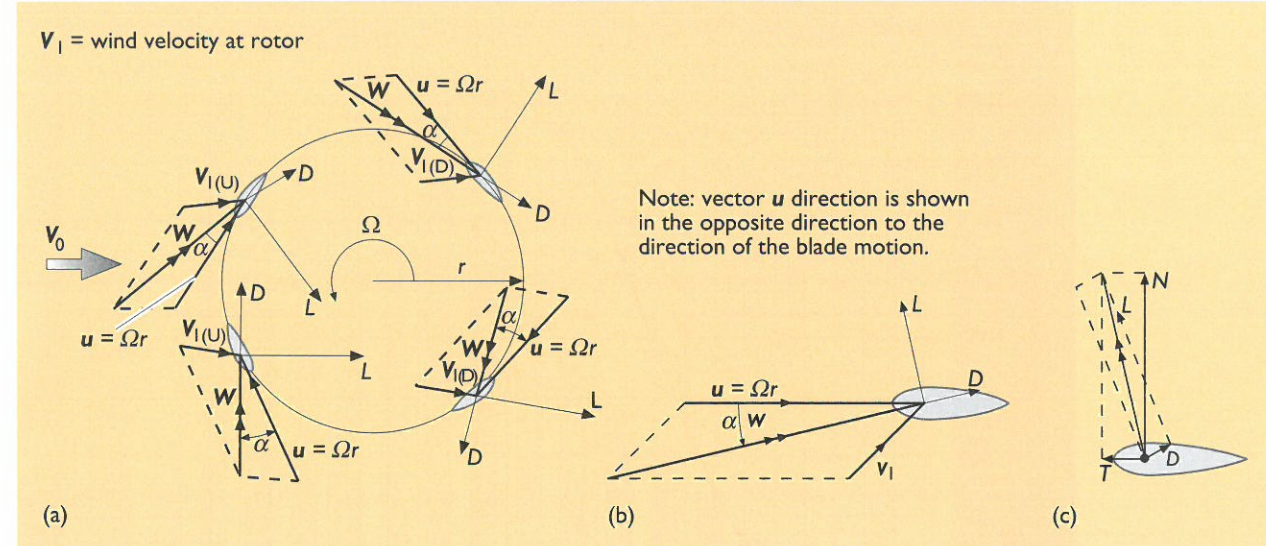


Figure 7.27 The lift and drag forces acting on VAWT rotor blades can be resolved into two components: 'normal', N, (that is, in line with the radius) and 'tangential', T, (that is perpendicular to the radius). The magnitude of both components varies as the angle of attack varies: (a) blade forces and relative velocities for a VAWT, showing angles of attack at different positions; (b) detail of aerodynamic forces on a blade element of a VAWT rotor blade; (c) normal (radial) and tangential (chord-wise) components of force on a VAWT blade. Note $V_{l(U)}$ is the wind velocity at the rotor on the upwind side; $V_{l(D)}$ is the wind velocity at the rotor on the downwind side

7.5 Power and energy from wind turbines

How much power does a wind turbine produce?

The power output of a wind turbine varies with wind speed: every turbine has a characteristic wind speed–power curve, often simply called the **power curve**. The shape of a wind speed-power curve is influenced by the:

- rotor swept area
- choice of aerofoil
- number of blades
- blade shape
- optimum tip speed ratio
- speed of rotation
- cut-in wind speed (the wind speed at which a turbine begins to generate power)
- rated wind speed (the wind speed at which a turbine generates its rated power)
- shut-down or cut-out wind speed (the wind speed at which a turbine is shut down and stops generating – also known as the furling wind speed)
- aerodynamic efficiency (power coefficient)
- gearing efficiency, and
- generator efficiency.

An example of such a curve is shown in Figure 7.28.

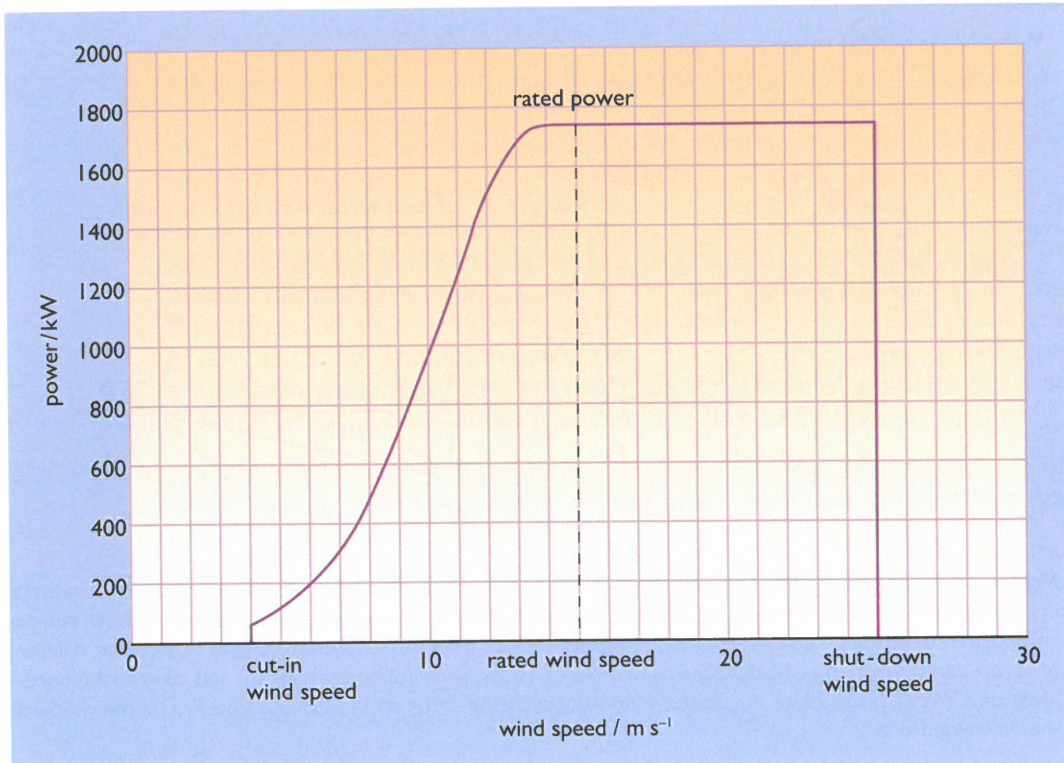


Figure 7.28 Typical wind turbine wind speed–power curve

How much energy will a wind turbine produce?

The energy that a wind turbine will produce depends on both its wind speed–power curve and the **wind speed frequency distribution** at the site. The latter is essentially a graph or histogram showing the number of hours for which the wind blows at different wind speeds during a given period of time. Figure 7.29 shows a typical wind speed frequency distribution.

For each incremental wind speed within the operating range of the turbine (that is, between the cut-in wind speed and the shut-down wind speed), the energy produced at that wind speed can be obtained by multiplying the number of hours of its duration by the corresponding turbine power at this wind speed (given by the turbine's wind speed–power curve). This data can then be used to plot a **wind energy distribution** such as that shown in Figure 7.30. The total energy produced in a given period is then calculated by summing the energy produced at all the wind speeds within the operating range of the turbine.

The best way to determine the wind speed distribution at a site is to carry out wind speed measurements with equipment that records the number of hours for which the wind speed lies within each given 1 m s^{-1} wide speed band, e.g. 0–1 m s^{-1}, 1–2 m s^{-1}, 2–3 m s^{-1}, etc.

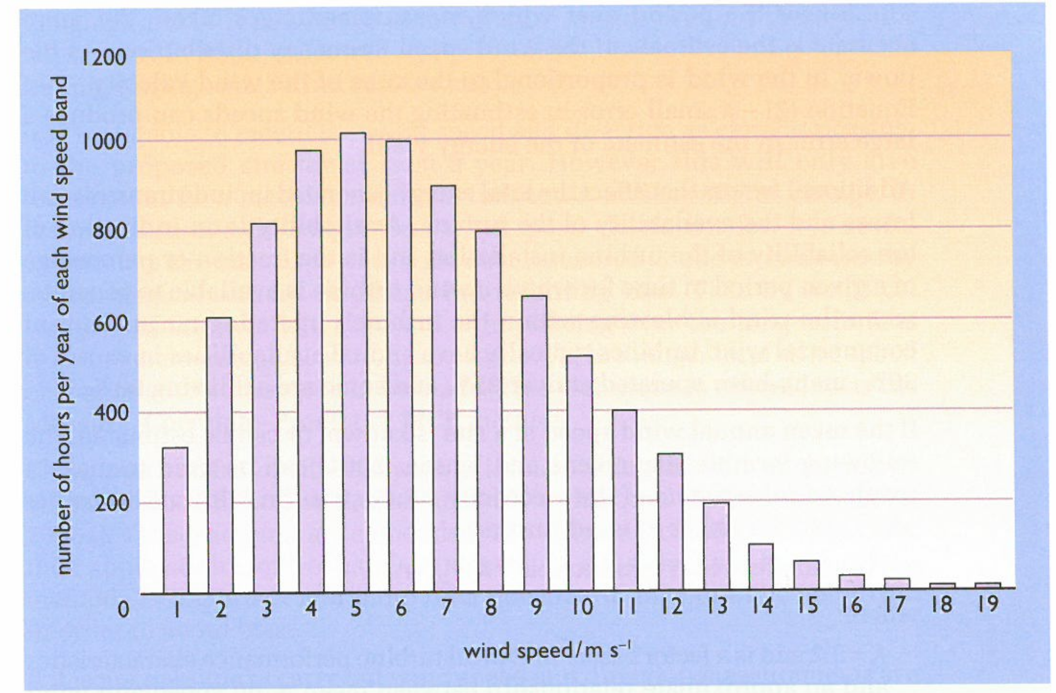


Figure 7.29 A wind speed frequency distribution for a typical site

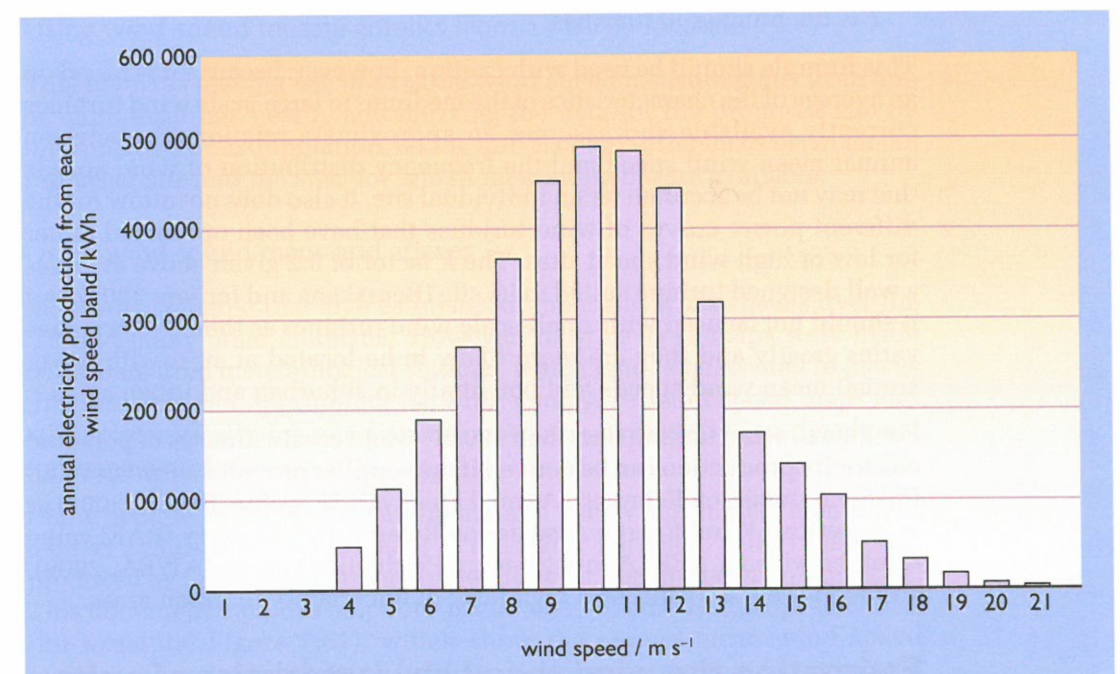


Figure 7.30 Wind energy distribution for the same site as in Figure 7.29, showing energy produced at this site by a wind turbine with the wind speed-power curve shown in Figure 7.28

The longer the period over which measurements are taken, the more accurate is the estimate of the wind speed frequency distribution. As the power in the wind is proportional to the cube of the wind velocity – see Equation (2) – a small error in estimating the wind speeds can produce a large error in the estimate of the energy yield.

Additional factors that affect the total energy generated include transmission losses and the availability of the turbine. **Availability** is an indication of the reliability of the turbine installation and is the fraction or percentage of a given period of time for which a wind turbine is available to generate, when the wind is blowing within the turbine's operating range. Current commercial wind turbines typically have annual availabilities in excess of 90%, many have operated at over 95% and some are achieving 98%.

If the mean annual wind speed at a site is known, or can be estimated, the following formula (Beurskens and Jensen, 2001) can be used to make a rough *initial estimate* of the electricity production (in kilowatt-hours per year) from a number of wind turbines:

Annual electricity production = $K\,V_m^3\,A_t\,T$

where:

$K = 3.2$ and is a factor based on typical turbine performance characteristics and an approximate relationship between mean wind speed and wind speed frequency distribution (see below)

V_m is the annual mean wind speed at the site in metres per second

A_t is the swept area of the turbine in square metres

T is the number of turbines.

This formula should be used with caution, however, because it is based on an average of the characteristics of the medium- to large-scale wind turbines currently available and assumes an approximate relationship between annual mean wind speed and the frequency distribution of wind speeds that may not be accurate for an individual site. It also does not allow for the different power curves of wind turbines that have been optimized either for low or high wind speed sites. The K factor of 3.2 given above assumes a well designed turbine suited to its site (Beurskens and Jensen, 2001), but it should not be used with small-scale wind turbines as their performance varies greatly and they are more likely to be located at sites with lower annual mean wind speeds and potentially in suburban and urban areas.

For a small wind turbine (less than 200 m^2 swept area) estimates of potential electricity production can be derived if the supplier provides a British Wind Energy Association Reference Annual Energy (RAE) value (BWEA, 2008) or an American Wind Energy Association Rated Annual Energy (RAE) value together with an AEP (Annual Energy Production) curve (AWEA, 2009), although there will still be a high level of uncertainty in urban areas.

Estimating the wind speed characteristics of a site

It is expensive to carry out detailed measurements at a site and wind speed measurements are often not carried out for small wind turbine installations. However the use of remote sensing methods such as SODAR (SOnic Detection And Ranging) and Doppler LIDAR (LIght Detection And Ranging) makes it feasible to monitor wind speeds without the need for tall towers. In addition, lower cost instrumentation is becoming available for monitoring small wind turbine sites.

It is preferable to record the wind speed and direction as close as possible to the proposed site for at least a year. However this will only give information for a particular time period, and weather patterns change. In order to ascertain the longer term wind speed characteristics, it is useful to correlate the measured data with data measured at one or more nearby meteorological stations or other wind recording sites. Then by statistical analysis of the two data sets, and extrapolating over the long-term data from the meteorological station, an estimate of the longer term wind speed characteristics at the site can be made. This technique is referred to as the **Measure–Correlate–Predict** or **MCP** method.

There are a number of different ways of implementing the MCP methodology all based on different statistical analysis techniques (Rogers et al, 2005, 2006a). These methods are embedded into different software packages, but their application requires careful judgement – consistency in the use of the methods is important and more than one algorithm should be employed in order to avoid bias.

If it is not possible to carry out wind speed and direction measurements at a proposed site, or where a preliminary analysis is required prior to installing instrumentation, there are a number of techniques that can be employed to give an approximate estimate of the wind speed characteristics of a site.

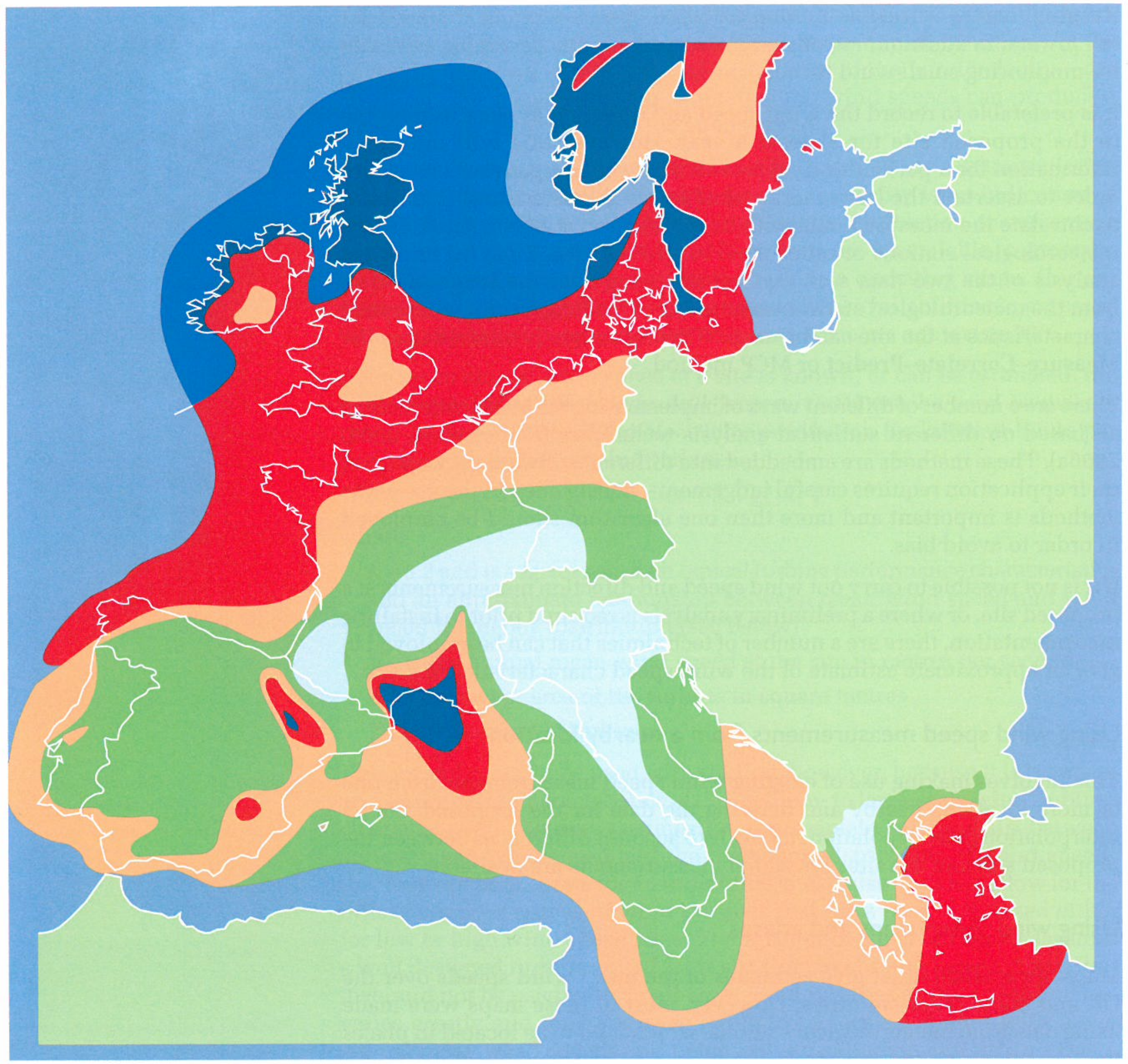
Using wind speed measurements from a nearby location

This involves making use of existing wind speed measurements from one or more locations nearby and deriving the data for the proposed site by interpolation or extrapolation, taking into account differences between the proposed site and the sites for which measurements are available.

Using wind speed maps and atlases

Maps are available that give estimates of the mean wind speeds over the UK and many other countries. However, most of these maps were made using data from meteorological stations, which tend to be located in places that are often not appropriate for wind energy, so wind speed maps and atlases specifically for wind energy purposes have also been developed for many countries.

Using long-term wind measurements and the WAsP model mentioned below, a *European Wind Atlas* (Troen and Petersen, 1989) has been produced by the Risø Laboratory in Denmark for the European Commission. This document includes maps of various areas within the European Union (for example, Figure 7.31), which show the annual mean wind speed at 50 m above ground level for five different topographic conditions: sheltered terrain, open plain, sea coast, open sea, hills and ridges. The atlas includes a series of procedures for taking account of site characteristics to estimate the wind energy likely to be available. These procedures work quite well on sites with a gentle topography but are not so good for very hilly terrain or urban areas. A similar atlas (included in Figure 7.31) has



Wind resources at 50 m above ground level for five different topographic conditions											
		Sheltered terrain		Open plain		At a sea coast		Open sea		Hills and ridges	
		m s^{-1}	W m^{-2}	m s^{-1}	W m^{-2}	m s^{-1}	W m^{-2}	m s^{-1}	W m^{-2}	m s^{-1}	W m^{-2}
Wind class	5	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1800
	4	5.0–6.0	150–250	6.5–7.5	300–500	7.0–8.5	400–700	8.0–9.0	600–800	10.0–11.5	1200–1800
	3	4.5–5.0	100–150	5.5–6.5	200–300	6.0–7.0	250–400	7.0–8.0	400–600	8.5–10.0	700–1200
	2	3.5–4.5	50–100	4.5–5.5	100–200	5.0–6.0	150–250	5.5–7.0	200–400	7.0–8.5	400–700
	1	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400

Figure 7.31 Annual mean wind speeds and wind energy resources over Europe (EU Countries) combining land-based and offshore wind atlases (source: Troen and Petersen, 1989)

also been produced to cover the *offshore* wind energy resource in the European Union (Risø, 2009). Similar wind atlases based on the same approach have also been produced for Russia, South Africa and parts of North Africa. Also wind speed/energy atlases have been produced for Ireland, USA and Canada.

The Energy Technology Support Unit (ETSU) also prepared a wind atlas and database of the UK. Using wind speed data from meteorological stations, a digital terrain model of the UK and a wind speed prediction computer model known as NOABL (Numerical Objective Analysis of Boundary Layer), ETSU estimated an annual mean wind speed (AMWS) value for each 1 km × 1 km Ordnance Survey grid square in the UK (Burch and Ravenscroft, 1992). Whilst this is a useful atlas/database for rural areas, it consistently over-predicts the AMWS in urban and suburban areas and (like most wind atlases developed for wind energy development in windy areas) it should not be used for that purpose. The UK Microgeneration Installation Standard, MIS 3003, (MIS, 2011 and MCS, 2011a), includes some adjustment factors that try to take account of this for small or micro wind turbines, but it is still not very reliable when used in those situations. This atlas is no longer being updated, but, at the time of writing, can still be accessed via the Renewable UK and Department for Climate Change (DECC) websites (Renewable UK, 2011a; DECC, 2011a).

Because of the unreliability of the NOABL database, the UK Energy Savings Trust has made available the wind speed data that it accumulated whilst carrying out field trials of domestic small wind turbines. This database of AMWS can be accessed by entering a UK post code together with the rural, suburban or urban site classification (EST, 2011).

For similar reasons the UK Carbon Trust commissioned the UK Meteorological Office to develop a new wind speed database derived from its own extensive wind speed data set together with a number of adjustments for urban and suburban locations. This can be accessed via the Carbon Trust's website (Carbon Trust, 2011) by entering the relevant OS grid reference or postcode together with a number of site classification parameters. It seems to be an improvement on the NOABL database for suburban and urban areas, but installing productive wind turbines in such locations still requires care.

Wind flow simulation computer models

A number of computer models have been developed that aim to predict the effects of topography on wind speed. Data from the nearest wind speed measurement station, together with a description of its site, is required and local effects are taken into account to arrive at estimated wind data for the proposed wind turbine site. Examples include NOABL and WAsP. As described above, NOABL was used in the development of the UK wind atlas/database and WAsP was used in the development of the *European Wind Atlas* (Figure 7.31). WAsP also forms the basis of at least two proprietary wind speed assessment computer software models. There are also improved versions of WAsP, for example for offshore use, and some that are better suited to modelling wind speeds in complex terrain.

CFD (computational fluid dynamics) is increasingly used to model wind flows in complex terrain, over and around forests and for designing wind farms. Berge et al., (2006) compares two CFD models with WAsP in modelling complex terrain.

Used with care, CFD models can be useful for carrying out initial assessments though they are complex, computer intensive, require training and need to be well understood. They tend to be used for wind farm projects in difficult terrain. There is also a need to have access to high quality digital terrain maps (special types of files containing three-dimensional map data), although some models are able to utilize/synchronize with Google Earth.

7.6 Environmental impact

Wind energy development has both positive and negative environmental impacts. The scale of its future implementation will rely on successfully maximizing the positive impacts whilst keeping the negative impacts to the minimum (see for example the US National Research Council's report for Congress, (NRC, 2007) which gives a comprehensive overview of the positive and negative environmental impacts of wind energy).

The generation of electricity by wind turbines does not involve the release of carbon dioxide or pollutants that cause acid rain or smog, that are radioactive, or that contaminate land, sea or water courses. Large-scale implementation of wind energy within the UK would probably be one of the most economic and rapid means of reducing carbon dioxide emissions. Over its working lifetime, a wind turbine can generate approximately 40 to 80 times the energy required to produce it (see Everett et al., 2012).

In addition, wind turbines do not require the consumption of water, unlike many conventional (and some renewable) energy sources. This benefit could be of growing importance if water shortages occur with increasing frequency in the future.

Of course wind power is not without certain negative (or perceived negative) repercussions and the following subsections will look into the following issues:

- noise
- electromagnetic interference
- aviation related issues
- wildlife
- public attitudes and planning.

Wind turbine noise

Whilst wind turbines are often described as noisy by opponents of wind energy, in general they are not especially noisy compared with other machines of similar power rating (see Table 7.1 and Figure 7.32). However, there have been incidents where wind turbine noise has been cited as a nuisance. Currently available modern wind turbines are generally much quieter than their predecessors and conform to noise immision level requirements (see below). **Noise immision** is a measure of the cumulative noise energy to which an individual is exposed over time. It is equal to the average noise level to which the person has been exposed, in decibels, plus 10 times the logarithm ($\log_{10}$) of the number of years for which the individual is exposed,

Table 7.1 Noise of different activities compared with wind turbines

Source/activity	Noise level in dB(A)*
Threshold of pain	140
Jet aircraft at 250 m	105
Pneumatic drill at 7 m	95
Truck at 48 km h^{-1} (30 mph) at 100 m	65
Busy general office	60
Car at 64 km h^{-1} (40 mph) at 100 m	55
Wind farm at 350 m	35–45
Quiet bedroom	20
Rural night-time background	20–40
Threshold of hearing	0

*dB(A): decibels (acoustically weighted to take into account that the human ear is not equally sensitive to all frequencies)
Source: ODPM, 2004b

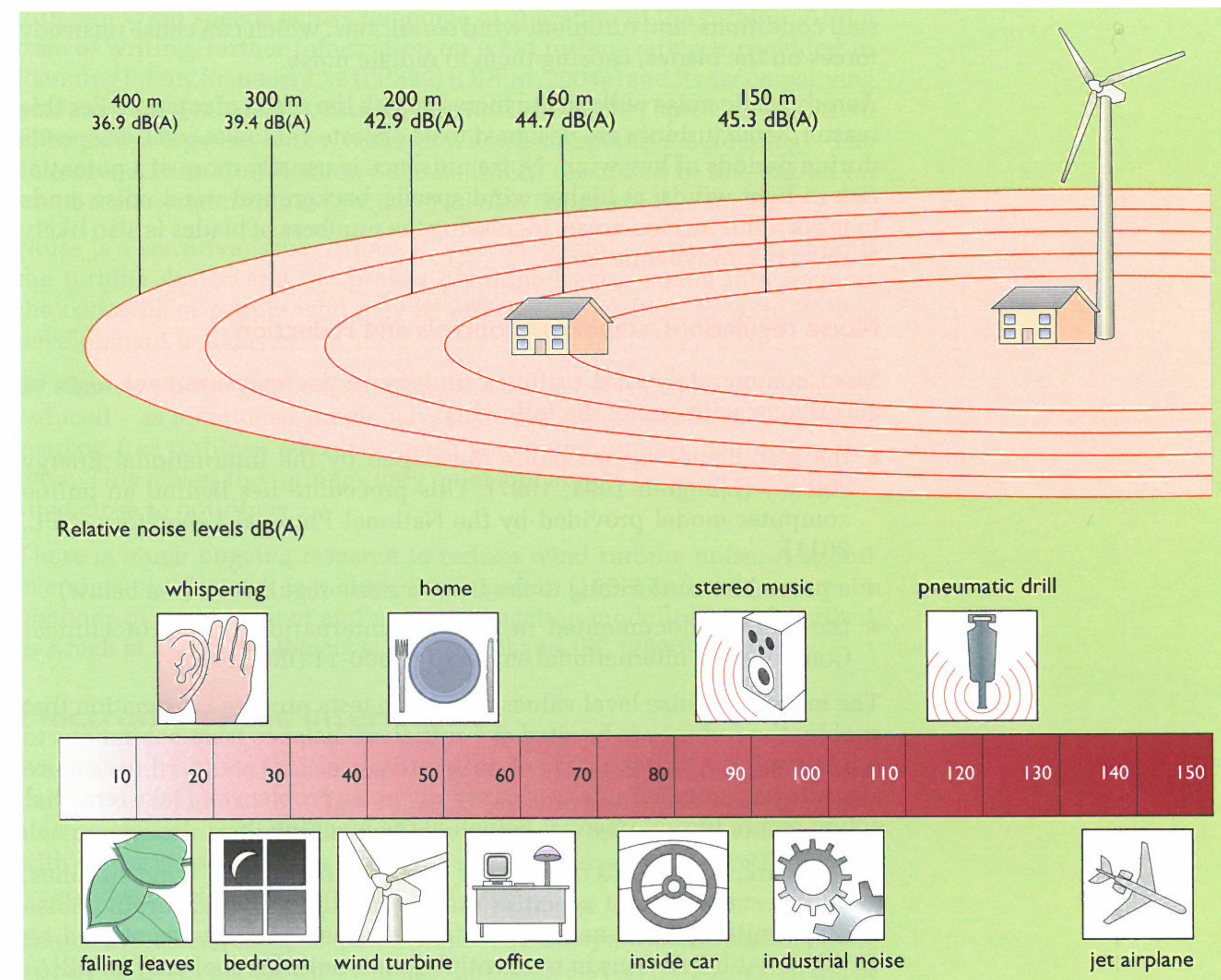


Figure 7.32 Wind turbine noise pattern from a typical wind turbine (source: EWEA, 1991)