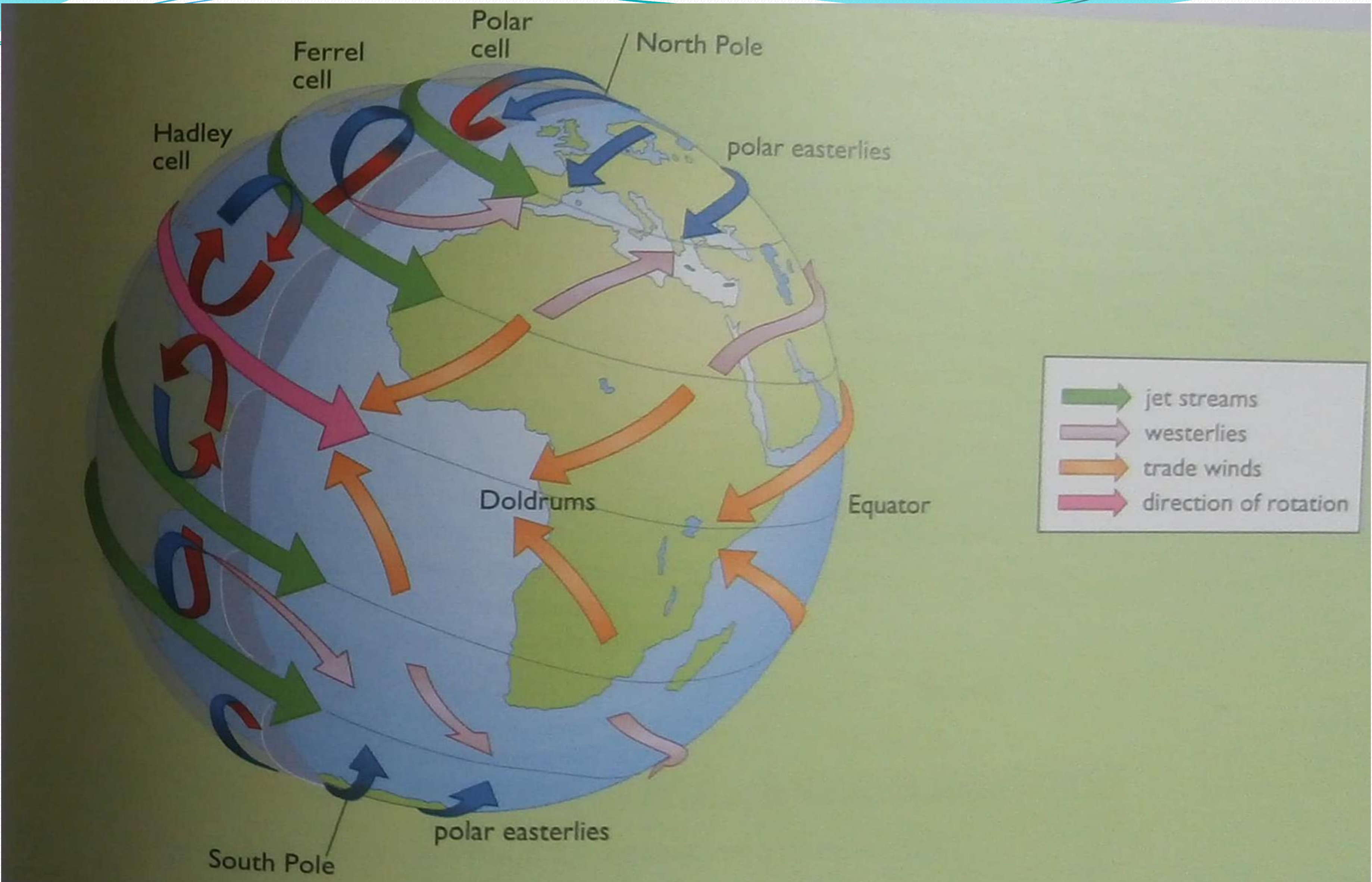


Figure 7.2 The global wind circulation (source: Burroughs et al., 1996)

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:

$$\text{kinetic energy} = \text{half mass} \times \text{velocity squared} = \frac{1}{2} m V^2 \tag{1}$$

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 $100 \times 10 = 1000$ 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* = $0.5\ \rho AV^3$ (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 7.5 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

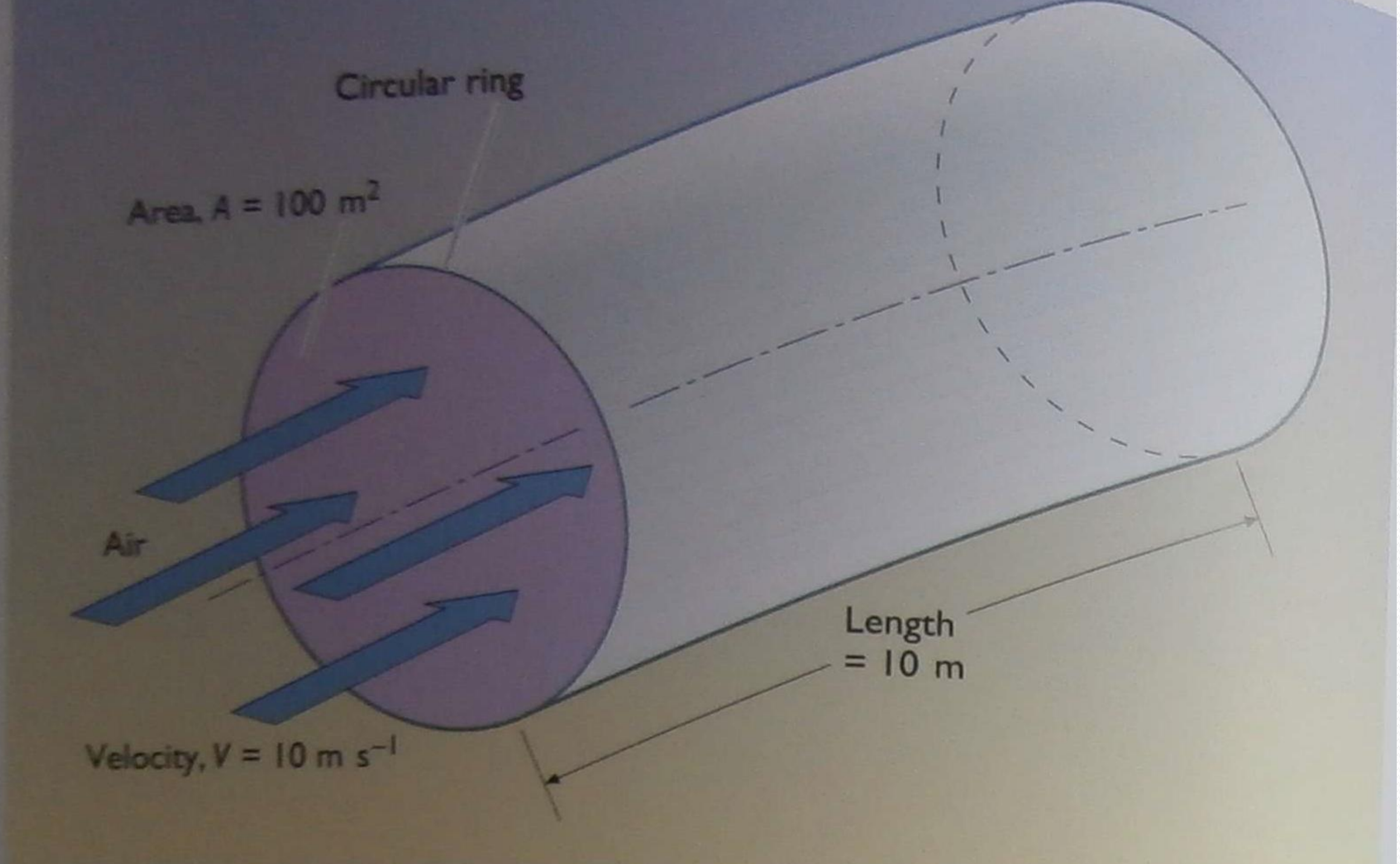
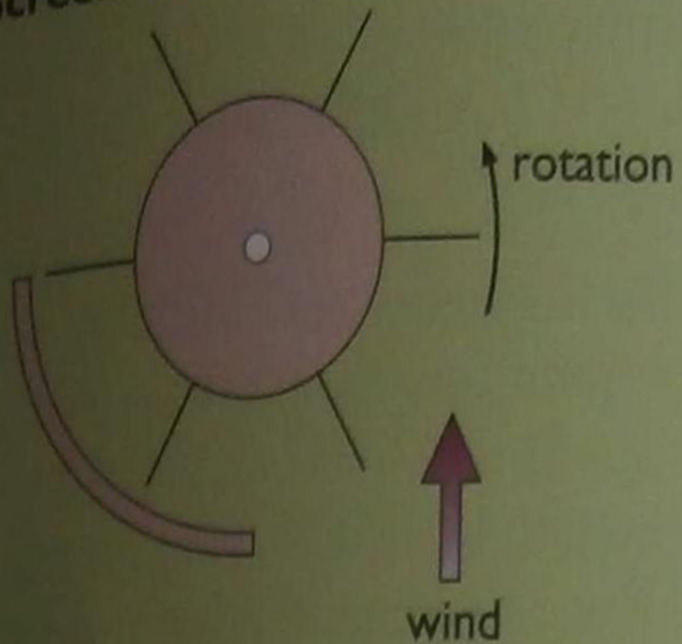
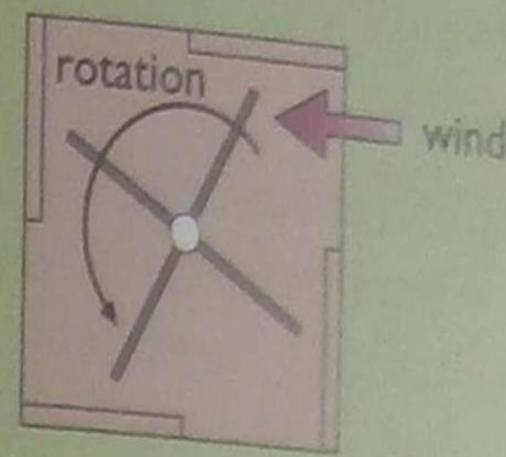


Figure 7.7 Cylindrical volume of air passing at velocity V ($10\ m\ s^{-1}$) through a ring enclosing an area, A ($100\ m^2$), each second

Screen wind machines



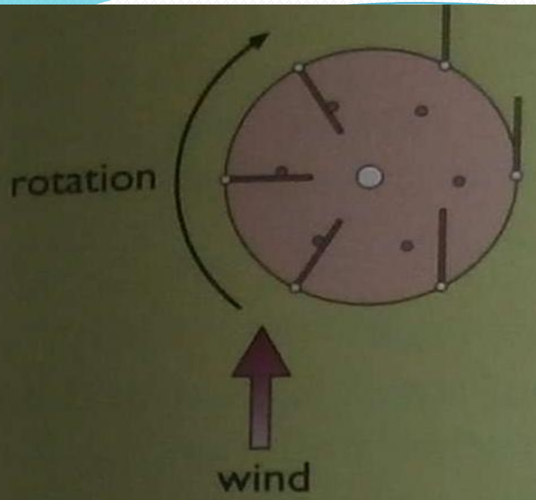
(a) screen

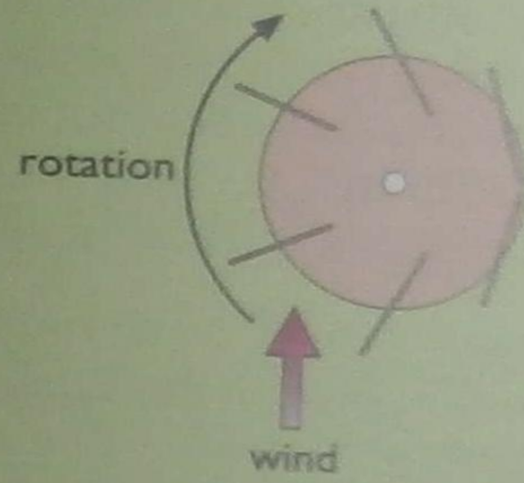


(b) vertical axis windmill screened by walls

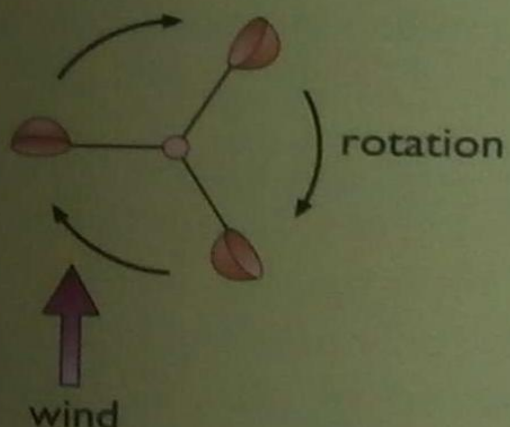
Clapper-type wind machines

Wind machine with cyclic pitch variation

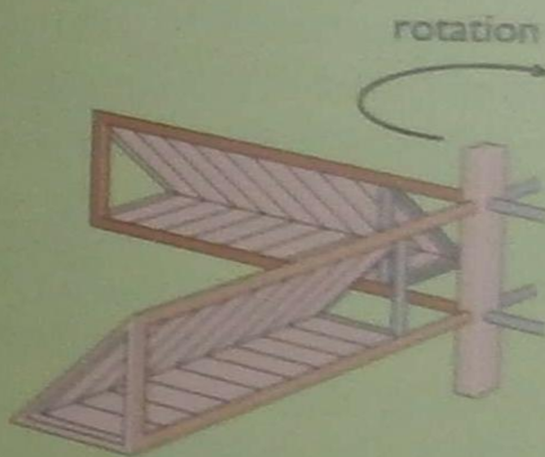




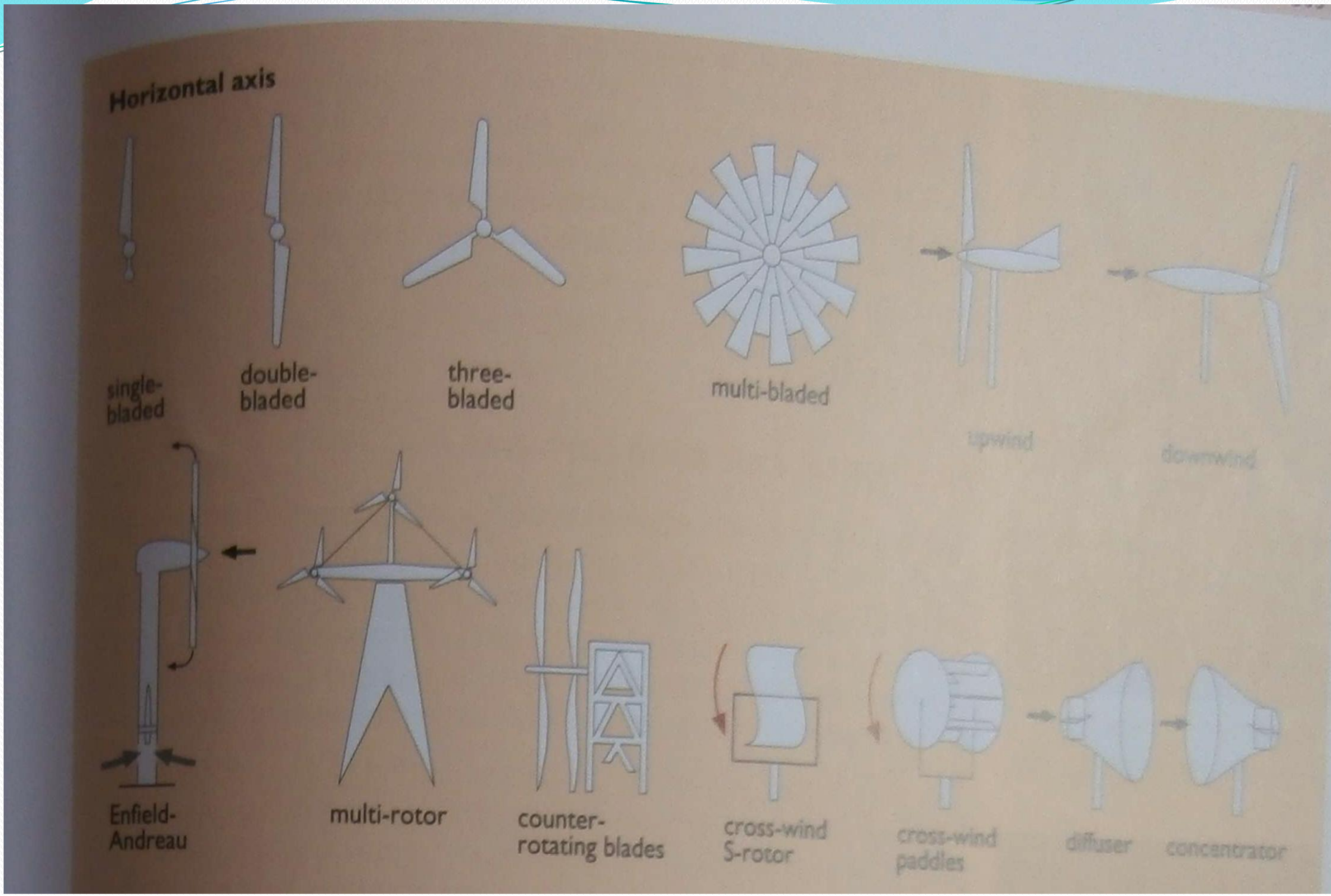
Cup-type wind machines

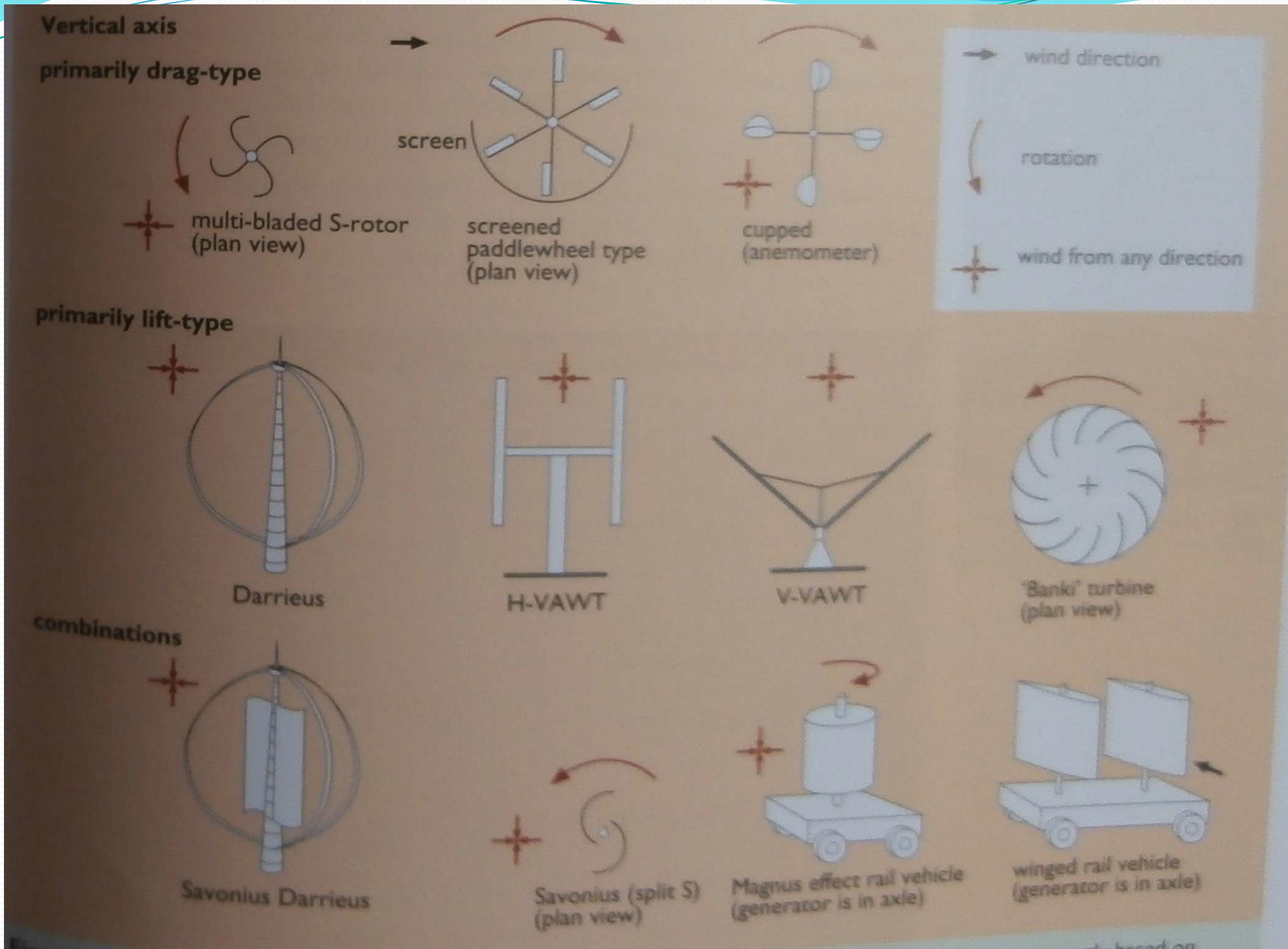


(a) cup anemometer



(b) 'streamlined anemometer sail windmill' invented by Faustus Verantius, a seventeenth century bishop and engineer (Needham, 1965)


Horizontal axis
single-bladed
double-bladed
three-bladed
multi-bladed
upwind
downwind
Enfield-Andreau
multi-rotor
counter-rotating blades
cross-wind S-rotor
cross-wind paddles
diffuser
concentrator


Vertical axis
primarily drag-type
screen
multi-bladed S-rotor
(plan view)
screened
paddlewheel type
(plan view)
cupped
(anemometer)
wind direction
rotation
wind from any direction
primarily lift-type
Darrieus
H-VAWT
V-VAWT
'Banki' turbine
(plan view)
combinations
Savonius Darrieus
Savonius (split S)
(plan view)
Magnus effect rail vehicle
(generator is in axle)
winged rail vehicle
(generator is in axle)

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**.

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

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.

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

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'.

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).

(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

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

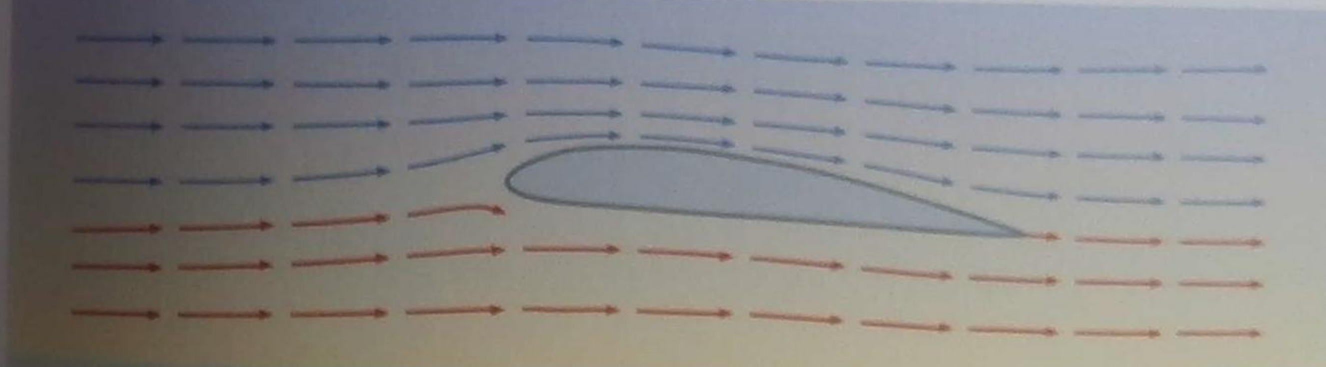


Figure 7.20 Streamlined flow around an aerofoil section

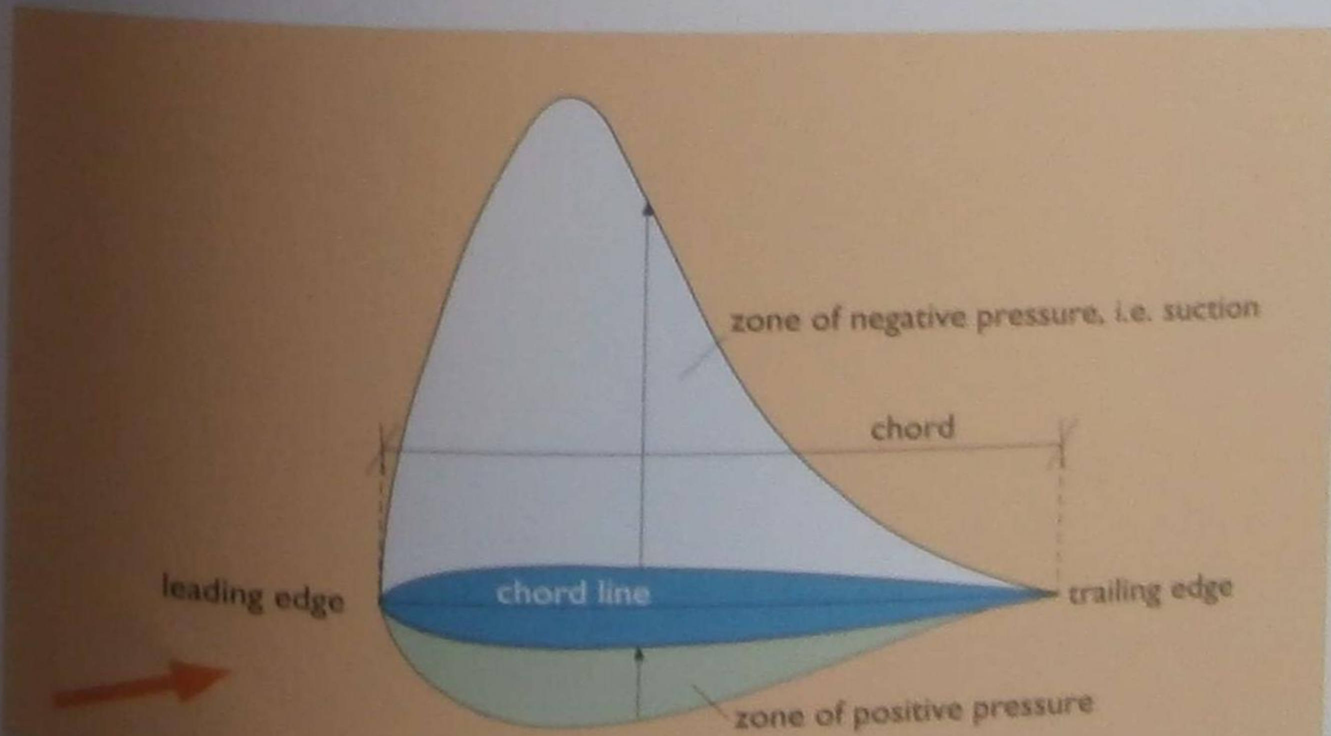


Figure 7.21 Zones of low and high pressure around an aerofoil section in an air stream

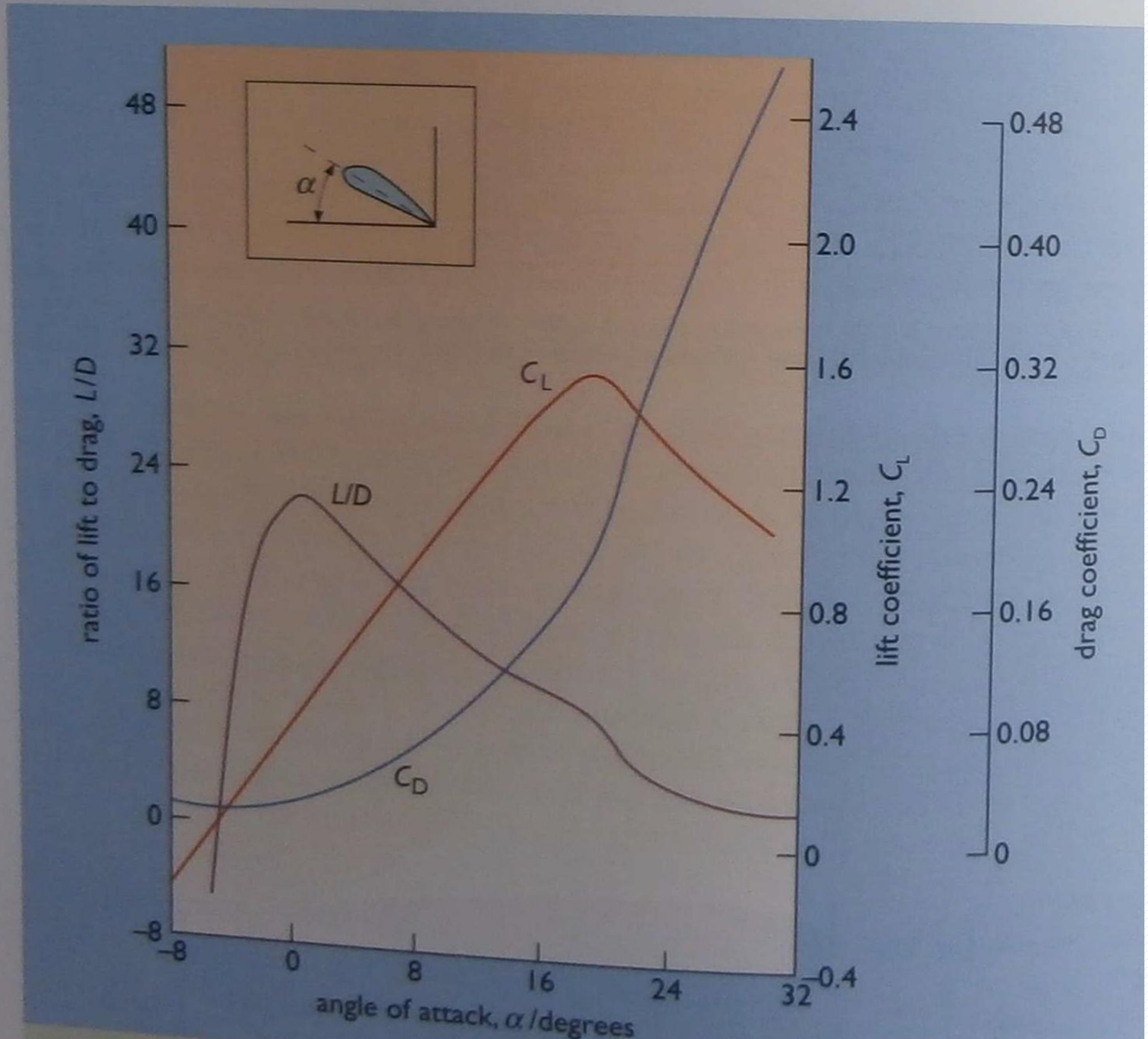


Figure 7.23 Lift coeffi...

Lift coefficient (C_L)

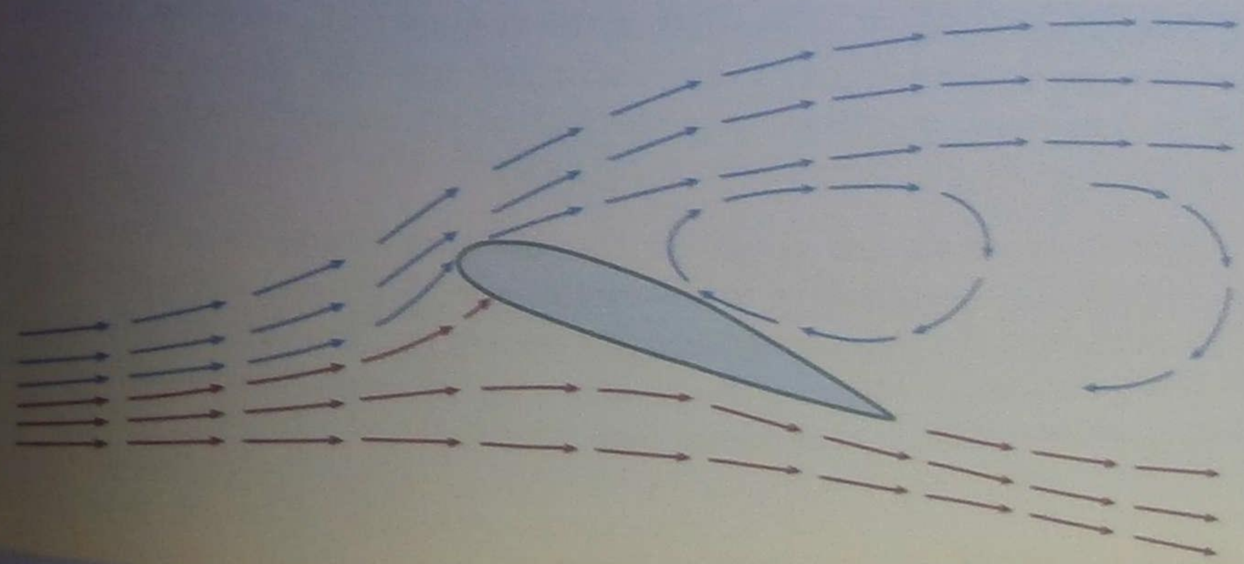
The lift coefficient of an aerofoil is given by the following expression:

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

where L is the lift force in newtons.

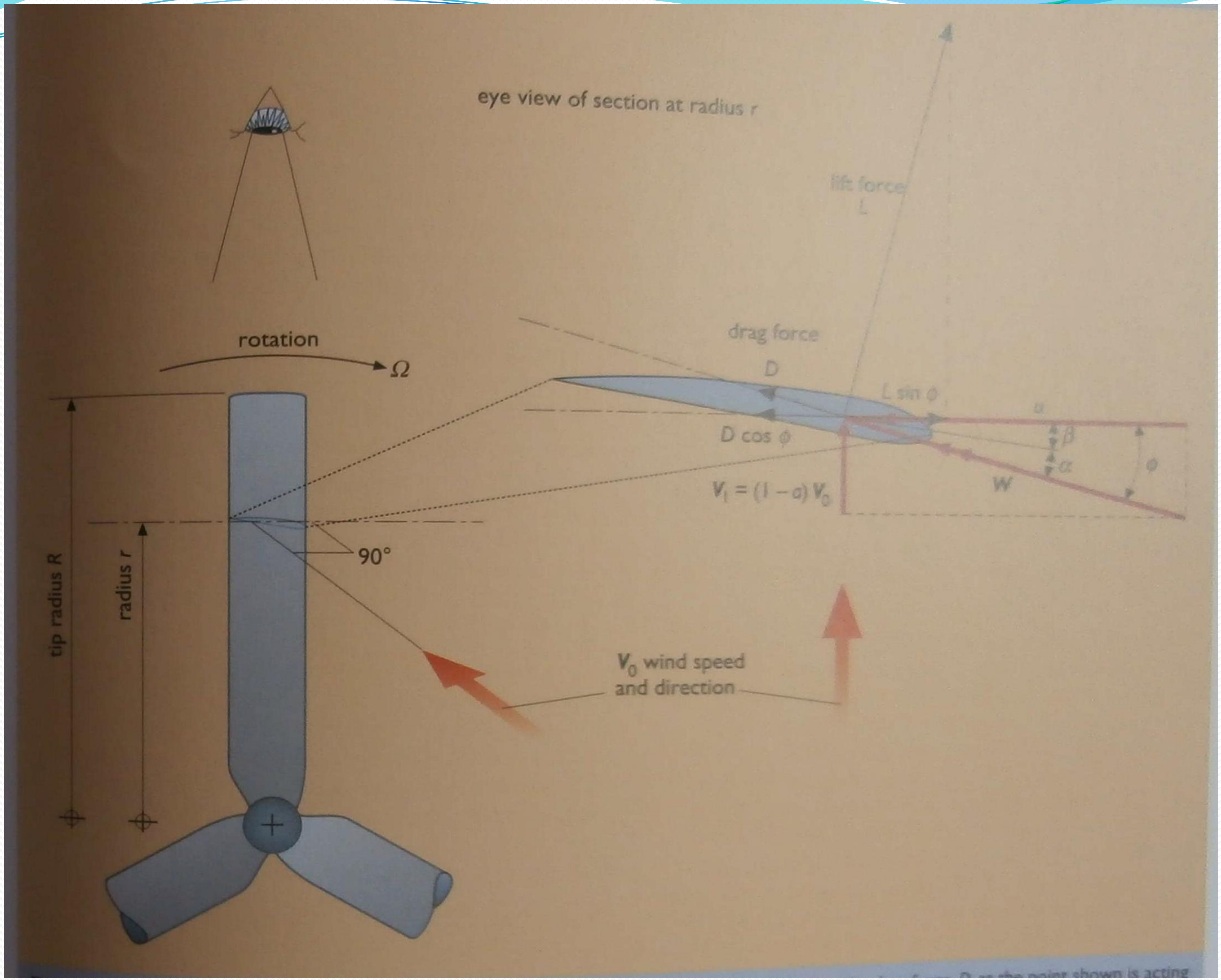
The lift and drag coefficients of an aerofoil can be measured in a wind tunnel at different angles of attack and wind velocities. The results of such measurements can be presented in either tabular or graphical form as in Figure 7.23.

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).



Relative wind velocity

When a wind turbine is stationary, the direction of the wind as 'seen' from a wind turbine blade is the same as the undisturbed wind direction. However, once the blade is moving, the direction from which it 'sees' the wind approaching effectively changes in proportion to the blade's velocity. (In the case of a moving vertical axis wind turbine blade, the direction from which the blade 'sees' the wind is also affected by its position during its rotation cycle – see Figure 7.27). Two-dimensional **vectors** are used to represent this effect graphically. A two-dimensional vector is a quantity that has both magnitude and direction. A velocity vector can be represented graphically in the form of an arrow, the length of which is proportional to speed, and the angular position of which indicates the direction of flow.


eye view of section at radius r
lift force
L
drag force
D
L sin ϕ
u
β
α
ϕ
D cos ϕ
W
$V_1 = (1 - a)\, V_0$
rotation
Ω
tip radius R
radius r
90°
V_0 wind speed
and direction

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.

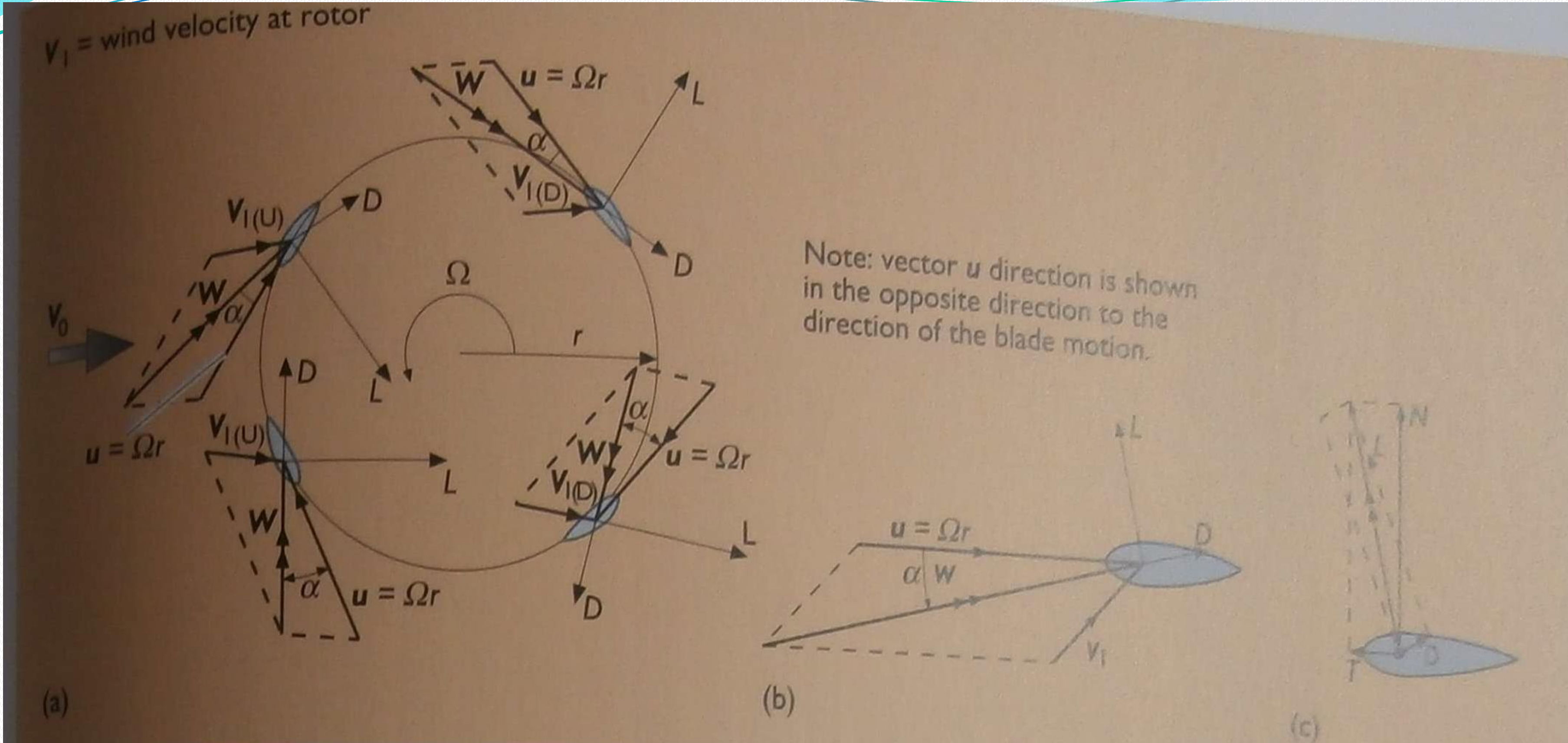


Figure 7.27 The lift and drag forces acting on VAWT rotor blades can be resolved into two components: 'normal', N, (that is, in line with the radius) and 'tangential', T, (that is perpendicular to the radius). The magnitude of both components varies as the angle of attack varies: (a) blade forces and 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 $V_{1(U)}$ is the wind velocity at the rotor on the upwind side; $V_{1(D)}$ is the wind velocity at the rotor on the downwind side

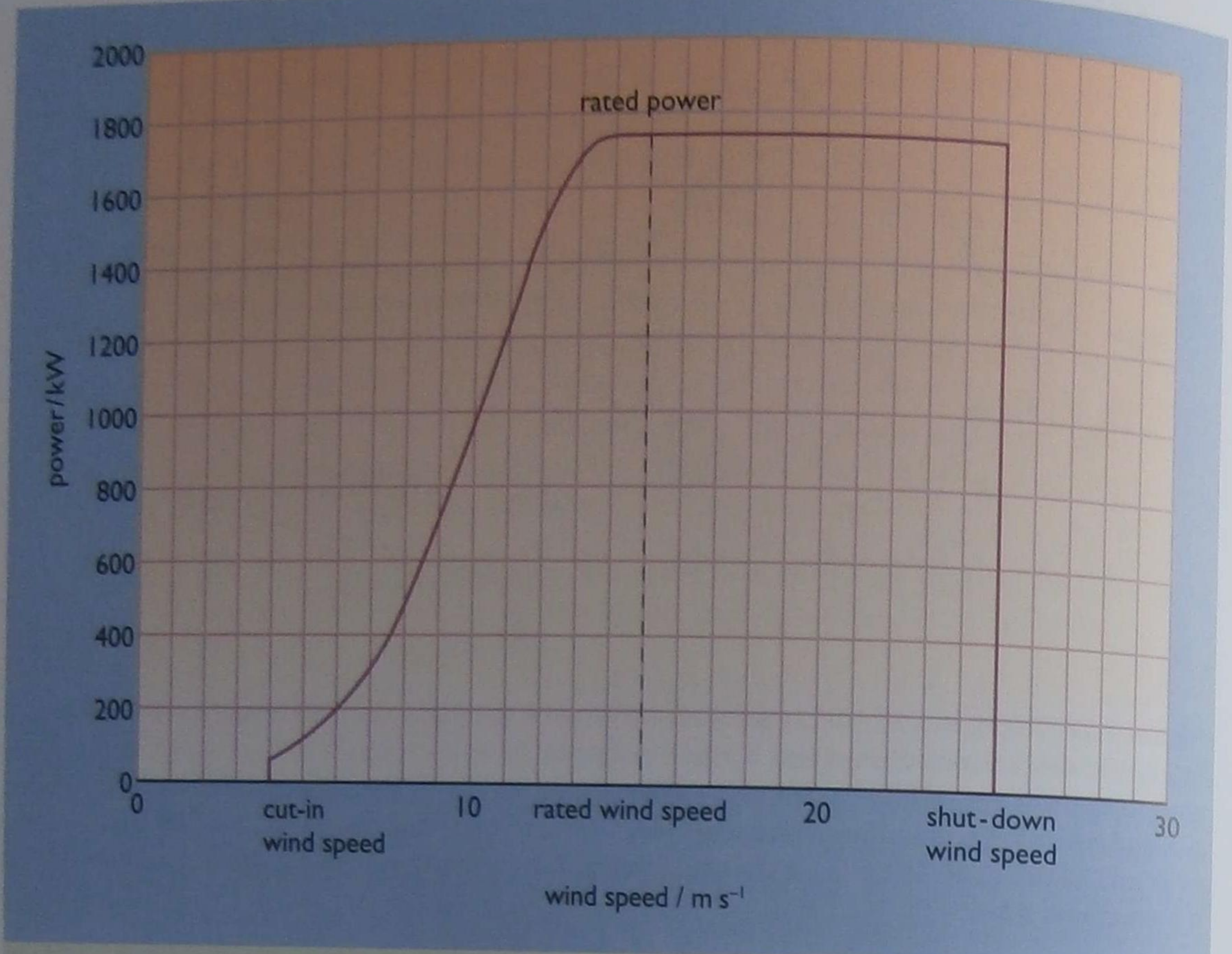


Figure 7.28 Typical wind turbine wind speed–power curve

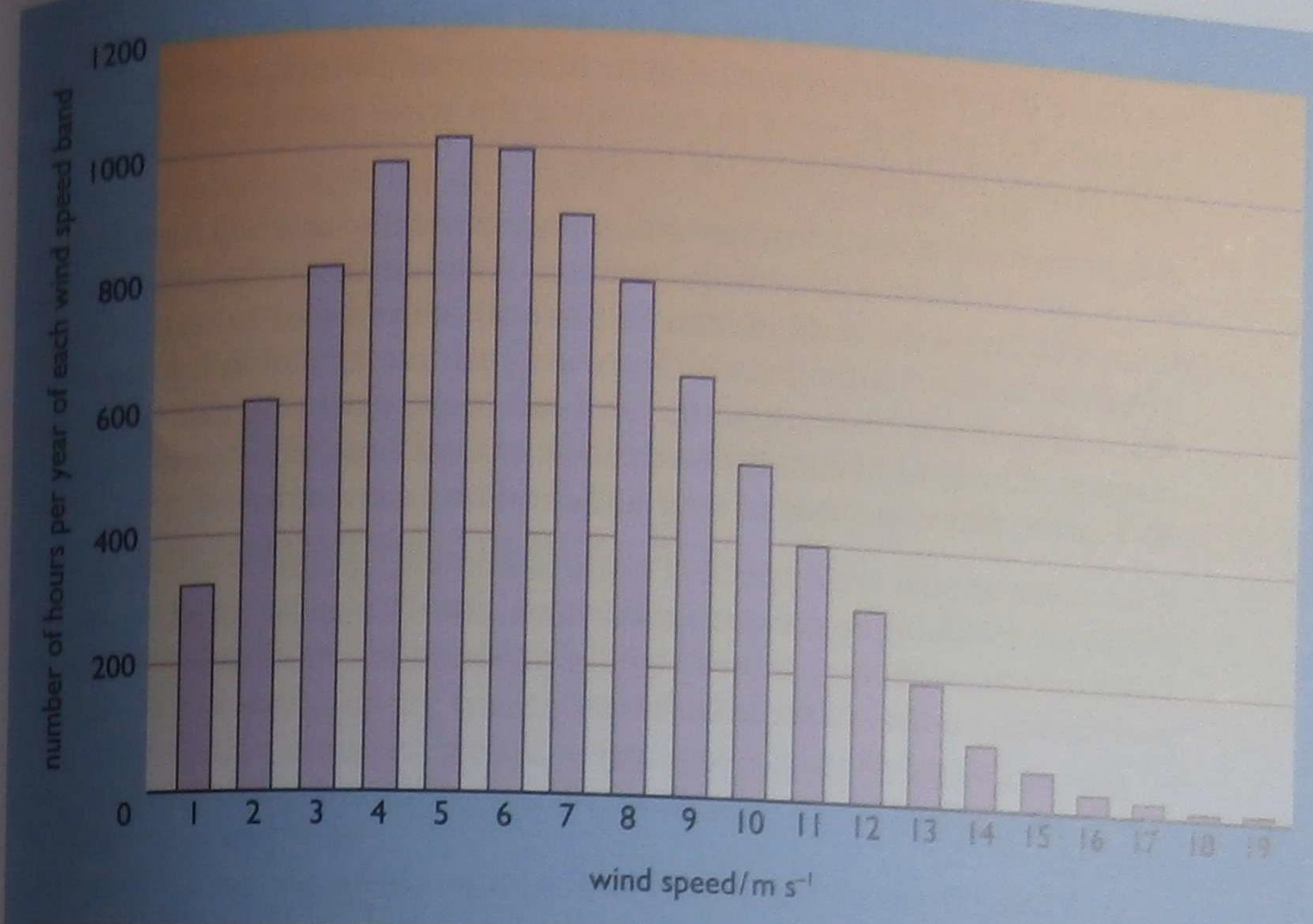


Figure 7.29 A wind speed frequency distribution for a typical site

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.

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

Noise regulations, standards, controls and reduction

Most commercial wind turbines undergo noise measurement tests in accordance with one of the following:

- the recommended procedure developed by the International Energy Agency (Ljungren 1994, 1997). This procedure lies behind an online computer model provided by the National Physical Laboratory (NPL, 2011)
- a procedure conforming to the Danish noise regulations (see below)
- the method documented in the IEC (International Electrotechnical Commission) international standard 61400-11 (IEC, 2006).

7.7 Economics

Calculating the costs of wind energy

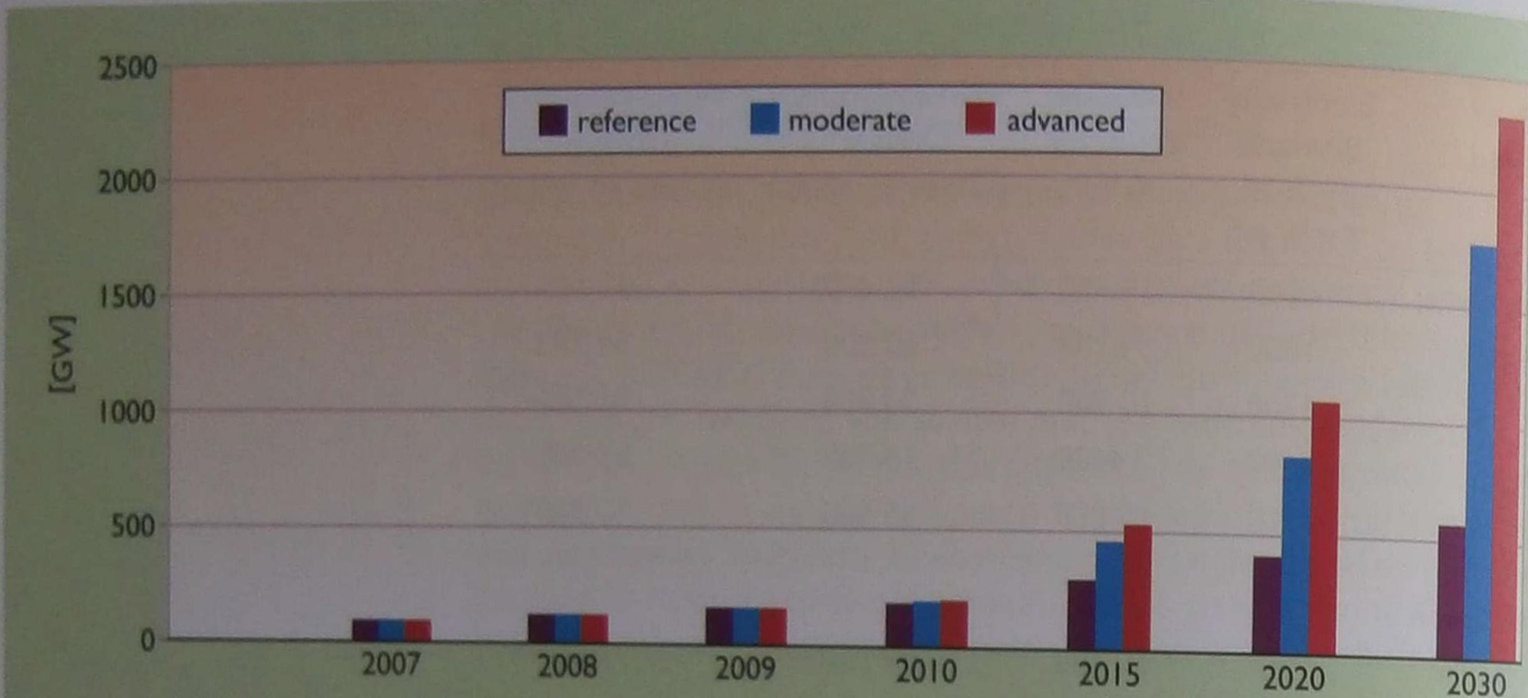
The economic appraisal of wind energy involves a number of specific factors. These include:

- the annual energy production from the wind turbine installation;
- the capital cost of the installation;
- the discount rate being applied to the capital cost of the project (see Chatper 10 and Appendix B);
- the length of the contract with the purchaser of the electricity being produced;
- the number of years over which the investment in the project is to be recovered (or any loan repaid), which may be the same as the length of the contract;
- the operation and maintenance costs, including maintenance of the wind turbines, insurance, land leasing, offshore leasing etc.

Table 7.3 Available world 'land-based' wind resources and future electricity demand

Region of the world	Electricity demand by 2025 TWh y^{-1}	Installed capacity GW	Wind resource TWh y^{-1} (Class 4+ sites)	Wind resource TWh y^{-1} (Class 3+ sites)
North America	6700	18 700	62 400	93 500
Latin America	1800	6100	20 400	36 300
Europe	6200	15 200	50 500	92 500
Western	3100	4400	14 700	21 000
Eastern and Former Soviet Union	3100	10 800	35 800	71 300
Africa/Middle East	2200	10 400	34 700	71 300
Asia	8700	1900	6400	21 500
India	1300			
China	4300			
Other Asia	3100			
Australia/Oceania	400	3200	10 700	20 200
World Total	**26 000**	**70 400**	**185 000**	**335 400**

Note: Class 4+ = Class 4 and above; Class 3+ = Class 3 and above
Source: Greenblatt, 2005



	2007	2008	2009	2010	2015	2020	2030
reference [MW]	93,864	120,297	158,505	185,258	295,783	415,433	572,733
[TWh]	206	263	347	406	725	1,019	1,405
moderate [MW]	93,864	120,297	158,505	198,717	460,364	832,251	1,777,550
[TWh]	206	263	347	435	1,129	2,041	4,360
advanced [MW]	93,864	120,297	158,505	201,657	533,233	1,071,415	2,341,984
[TWh]	206	263	347	442	1,308	2,628	5,429

Figure 7.39 Global cumulative wind power capacity to 2030 (source: GWEC, 2010)

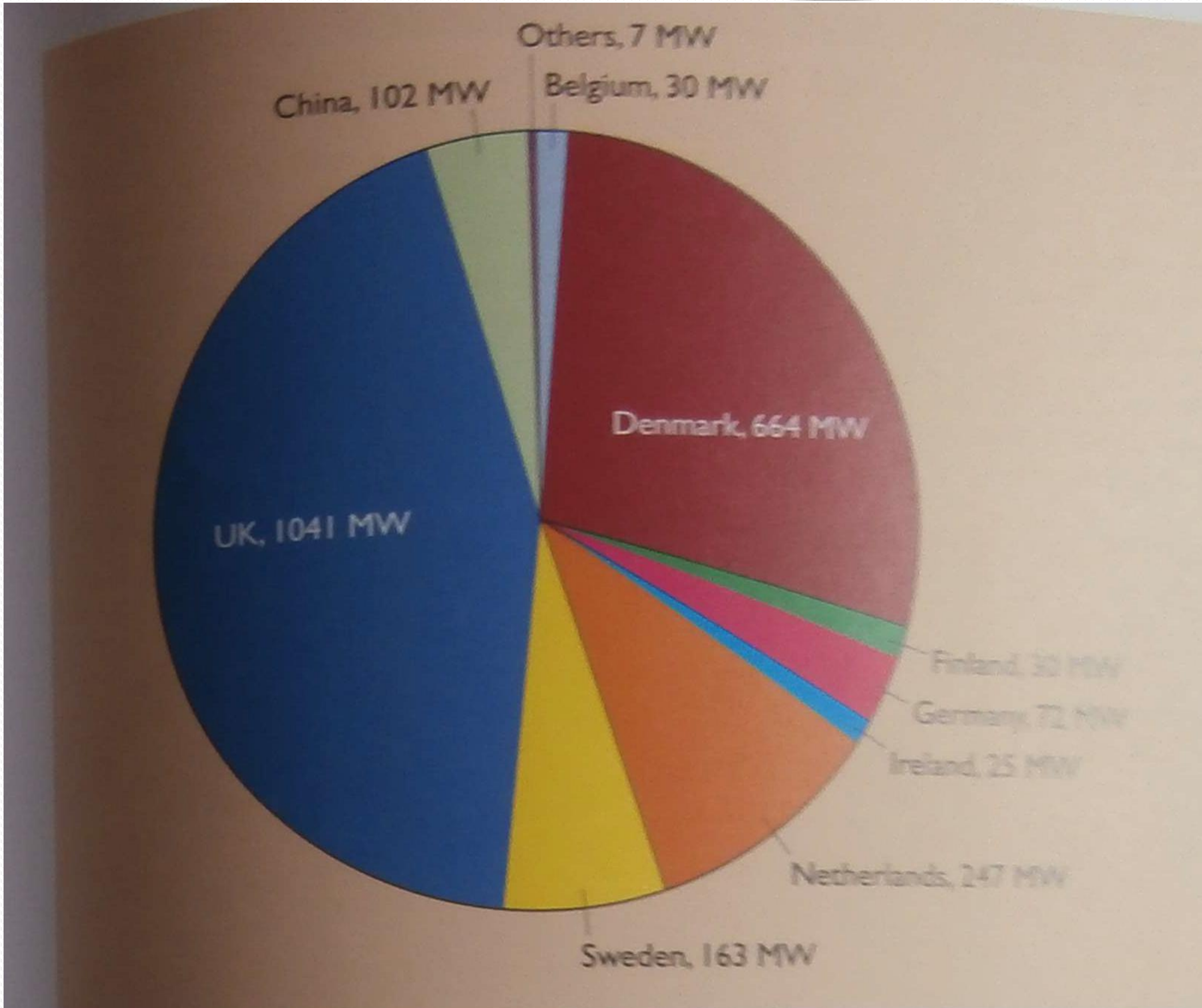


Figure 7.42 Global installed offshore wind energy capacity by country (January 2010) (sources: 4C Offshore Ltd, 2010; Musial and Ram, 2010)

(b)