Water power, like most renewable energy sources, is indirect solar power, and like others such as the wind, it has been contributing to local energy supplies for many centuries. It is, however, unique in that it became a major 'modern' energy source over a hundred years ago, supplying the input for some of the earliest power stations. Hydroelectricity has become a well-established technology, delivering (at the time of writing) about a sixth of the world's annual electricity supply (Figure 5.1).

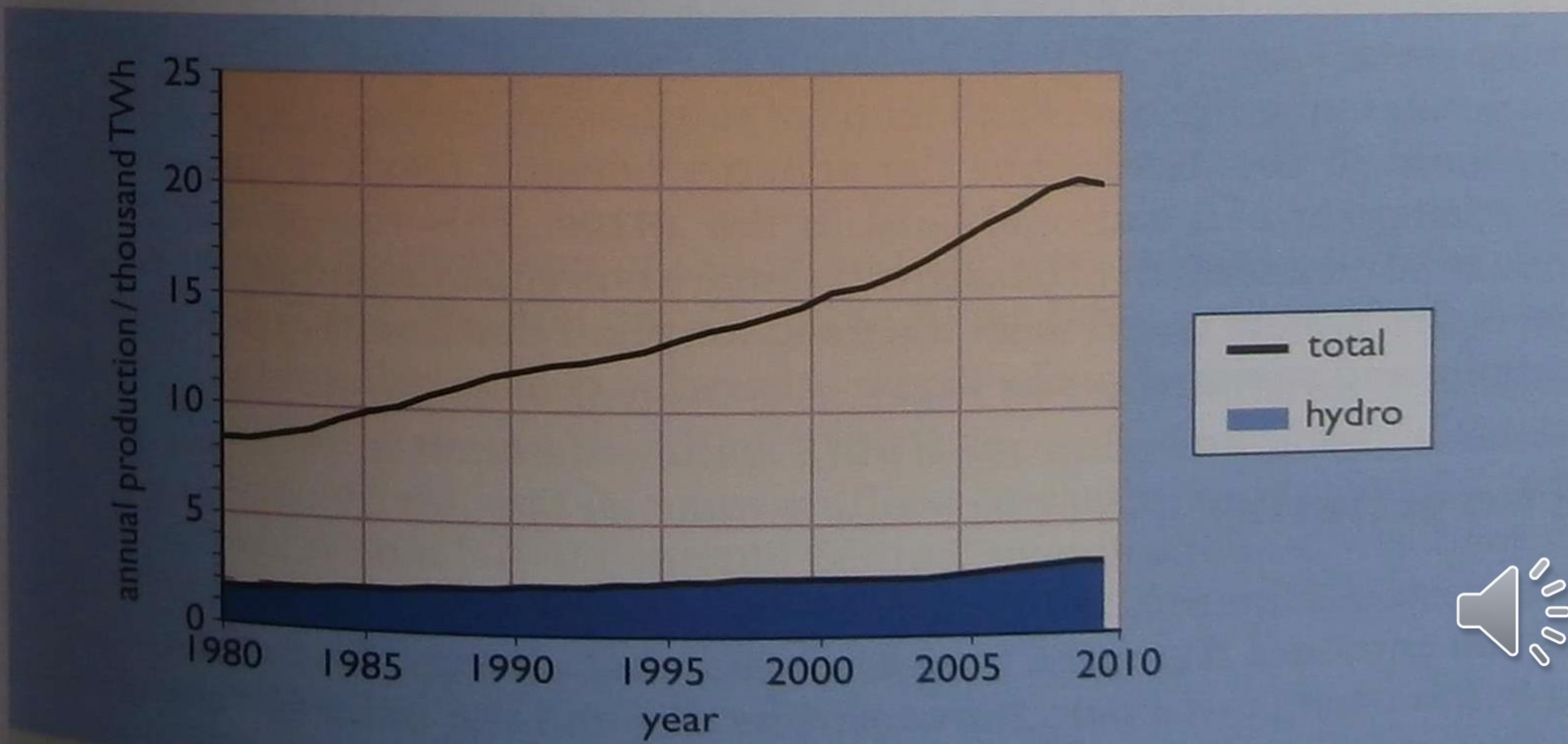


Figure 5.1 World total electricity production and hydro contribution, 1980–2009 (source: BP, 2010)

Power

The essential characteristics of a hydro site are the **effective head** (H), the height in metres through which the water falls, and the **flow rate** (Q), the number of cubic metres of water passing through the plant per second. As we shall see in Section 5.5, there is a simple approximate relationship between these two quantities and the power delivered by the water (P), measured in kilowatts (kW):

$$P\,(\text{kW}) = 10 \times Q \times H$$

The turbines

The head and the required power are critical in determining the most suitable type of turbine for a site. Glenlee's high head puts it at one extreme in the Galloway system, with Drumjohn's very low head and power rating at the other. Of the four river plants, Kendoon and Tongland have intermediate heads and fairly high power ratings whilst Carsfad and Earlstoun have almost identical low heads and powers.

Any turbine consists of a set of curved blades designed to deflect the water in such a way that it gives up as much as possible of its energy. The blades and their support structure make up the turbine **runner**, and the water is directed on to this either by channels and guide vanes or through a jet, depending on the type of turbine. The Galloway plants include two types of runner: 'propellers' and Francis turbines (see Figure 5.17). As discussed in more detail later, 'propeller' types are most suitable for large flows at low heads, and Francis turbines for medium to high heads. Comparison of Tables 5.1 and 5.2 shows that this is true for the Galloway scheme.

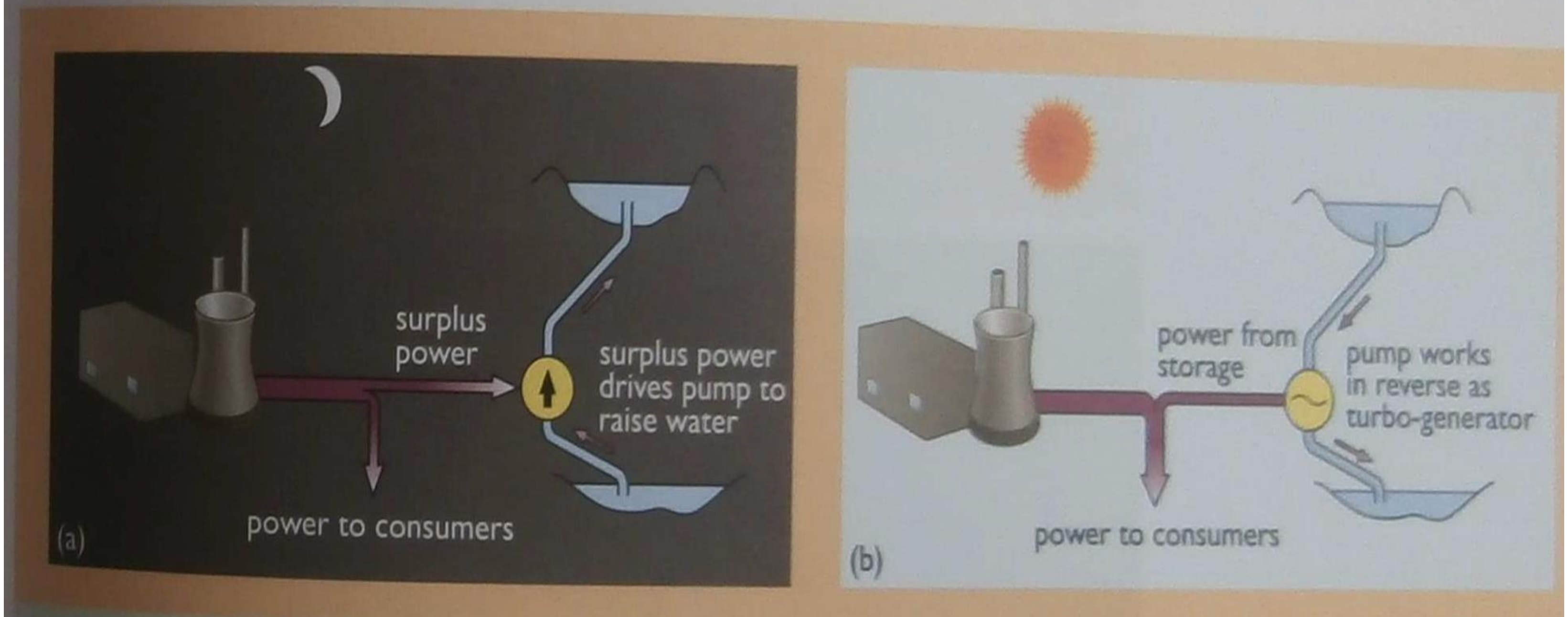
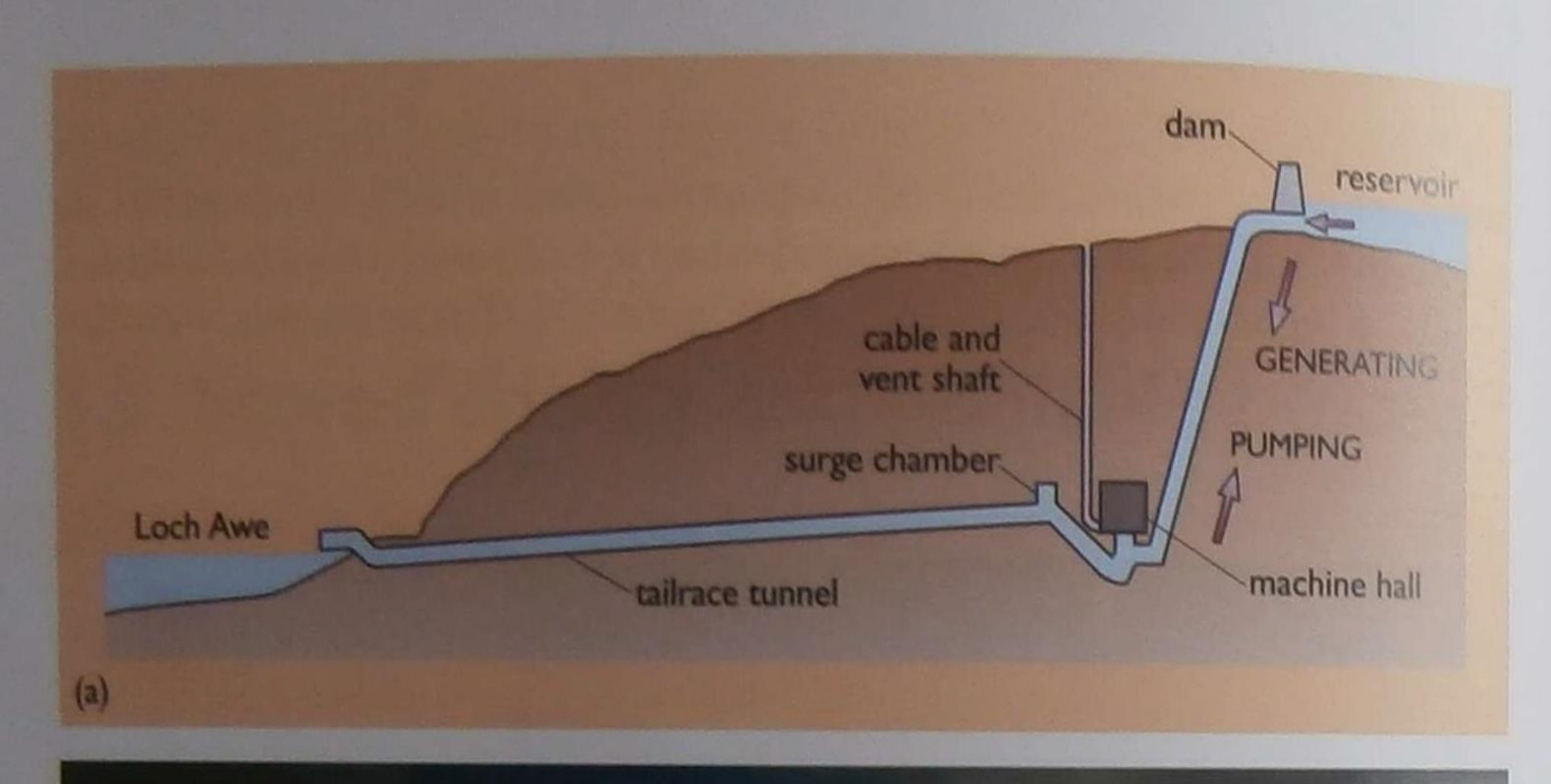


Figure 5.7 Pumped storage system (a) at time of low demand, (b) at time of high demand


dam
reservoir
GENERATING
PUMPING
cable and
vent shaft
surge chamber
Loch Awe
tailrace tunnel
machine hall
(a)

Power, head and flow rate

In estimating the value of any proposed hydroelectric plant, the *power* available at any time is probably the most important factor. The power supplied by a plant, the number of *watts*, is the rate at which it delivers energy: the *number of joules per second*. This will obviously depend on the **volume flow rate** of the moving water. Note that this is not just the speed of the water; it is the number of *cubic metres per second* passing through the plant, usually represented by the symbol Q (think quantity).

It then follows from Equation (1) above that the power P (in watts), which is the energy per second, will be

$$P = 1000 \times Q \times g \times H \qquad (2)$$

5.7 Types of hydroelectric plant

Present-day hydroelectric installations range in capacity from a few hundred watts to more than 10 GW – a factor of some hundred million between the smallest and the largest output. We can classify installations in different ways:

- by the effective head of water
- by the capacity – the rated power output
- by the type of turbine used
- by the location and type of dam, reservoir, etc.

These categories are not of course independent of one another. The available head is an important determinant of the other factors, and the head and capacity together largely determine the type of plant and installation. We start therefore with the customary classification in terms of head, but shall soon see that it is really the fourth criterion that matters.

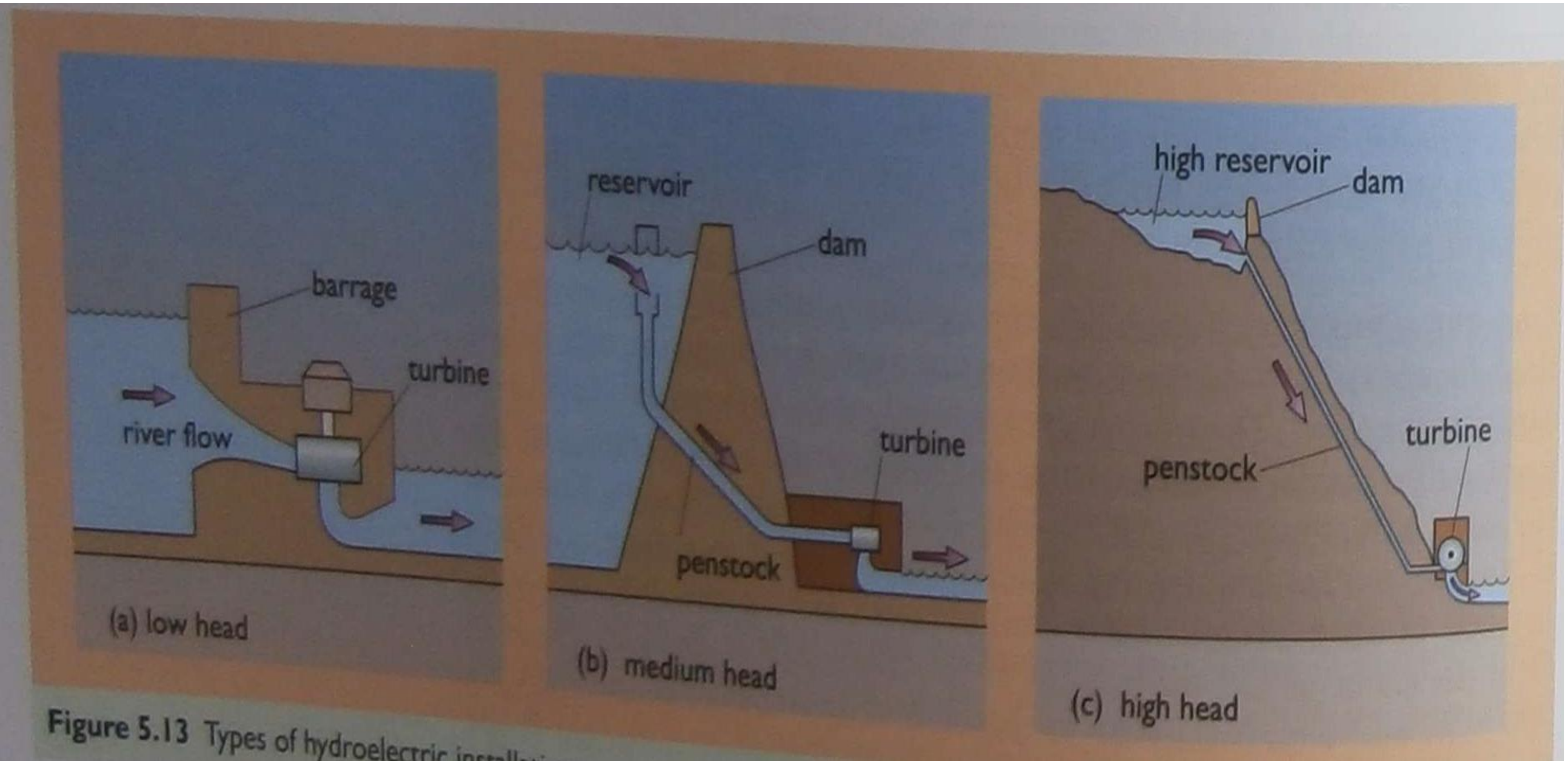


Figure 5.13 Types of hydroelectric

Low, medium and high heads

Two hydroelectric plants with the same power output could be very different: one using the huge volume flow of a slowly moving river and the other a relatively low volume of high-speed water from a mountain reservoir. Sites, and the corresponding hydroelectric installations, can be classified as *low*, *medium* or *high* head. The boundaries are fuzzy, and tend to depend on whether the subject of discussion is the civil engineering work or the choice of turbine; but **high head** usually implies an effective head of appreciably more than 100 metres and **low head** less than perhaps 10 metres. Figure 5.13 shows the main features of the three types.

Estimating the power

Reliable data on water flow rates and, equally important, their variations, is essential for the assessment of the potential capacity of a site. Stopping the flow and catching the water for a measured time is hardly practicable for large flows or as a routine method. The preferred techniques depend on establishing empirical relationships between flow rate and either water depth or water speed at chosen points. Simple depth or speed monitoring then provides a record of flow rates. For many major rivers, particularly in developed countries, such data has been accumulated for years.

Where such records are not available, an entirely different approach is to determine the annual precipitation over the catchment area. This gives the total flow into the system and is particularly suitable for large systems. However, allowance must be made for losses due to processes such as re-evaporation, take-up by vegetation or leakage into the ground, and as these could account for as much as three-quarters of the original total they are hardly negligible corrections.

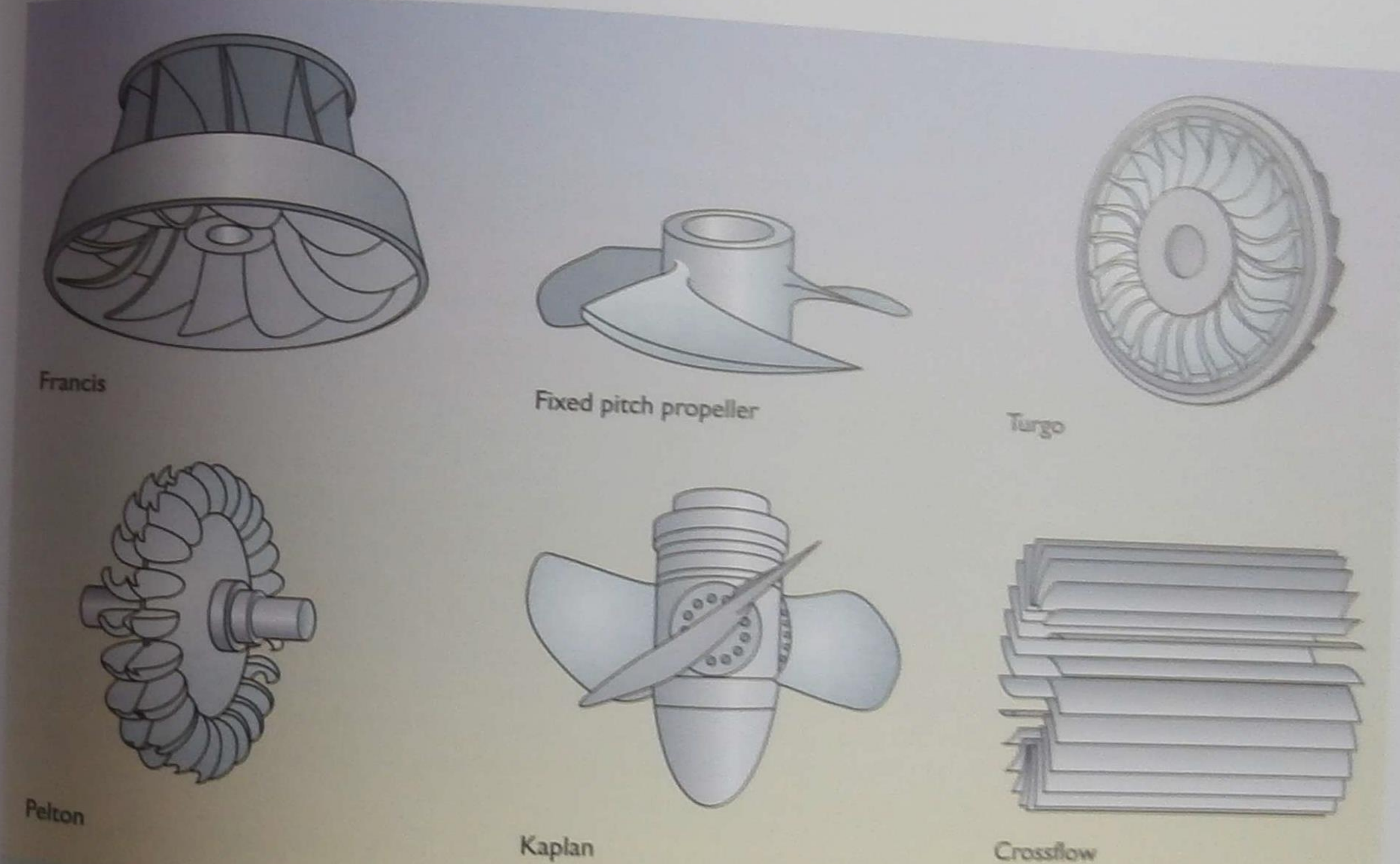


Figure 5.17 Types of turbine runner

Francis turbines

Francis turbines (Figures 5.17 to 5.20) are by far the most common type in present-day medium- or large-scale plants, being used in locations where the head may be as low as 2 m or as high as 300 m. They are radial-flow turbines, and although the water flow is inwards towards the centre instead of the outward flow of Fourneyron's turbine, the principle remains the same.

Action of the turbine

As the Francis turbine is completely submerged, it can run equally well with its axis horizontal (Figure 5.19) or vertical (Figure 5.20). In medium- or high-head turbines the flow is channelled in through a scroll case (also called the volute) a curved tube of diminishing size rather like a snail shell, with the guide vanes set in its inner surface. Directed by the guide vanes, the water flows in towards the runner. The shapes of the guide vanes and runner blades and the speed of the water are critical in producing the smooth flow that leads to high efficiency (see below). Francis turbines run most efficiently when the blade speed is only slightly less than the speed of the water meeting them.

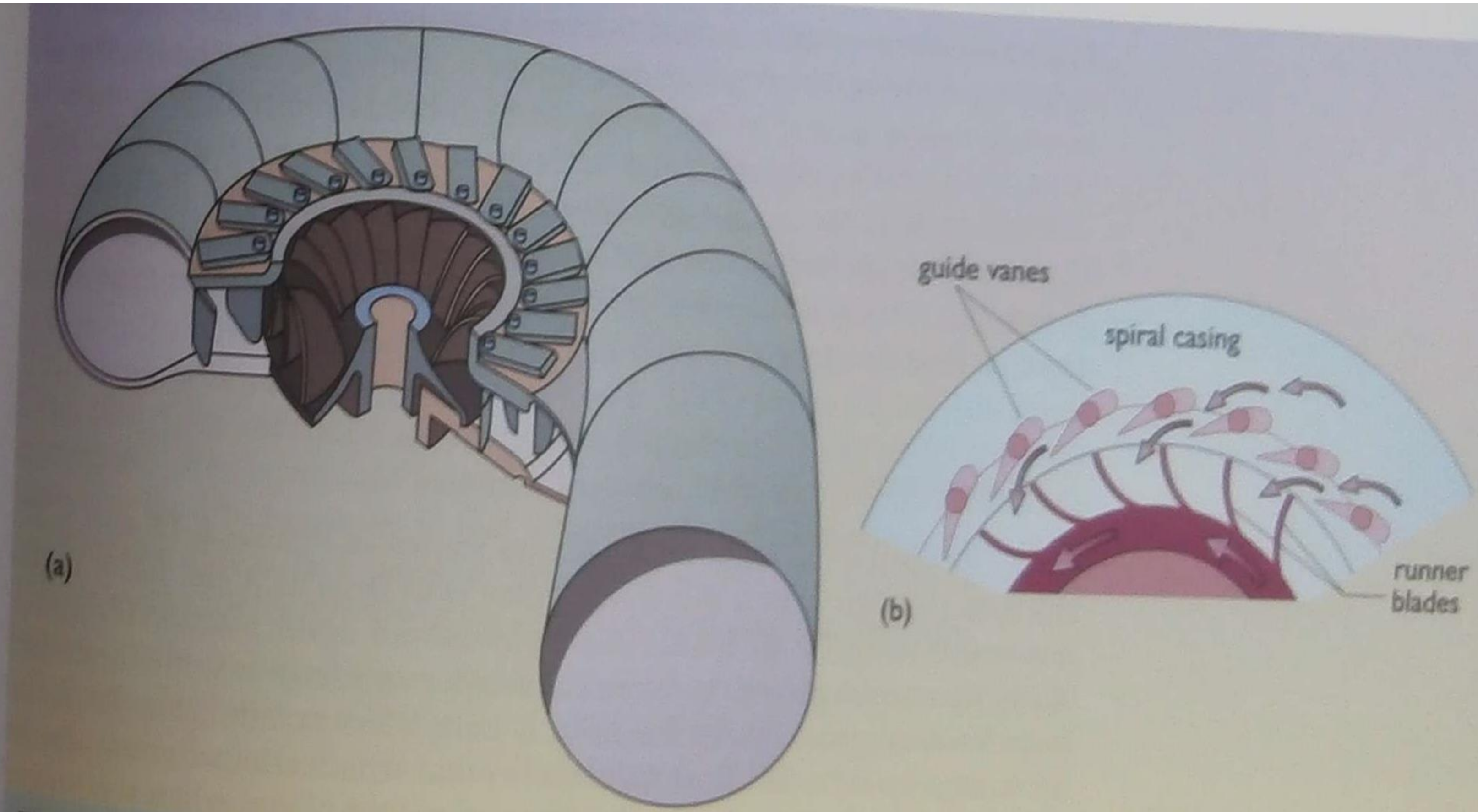


Figure 5.20 Structure of a Francis turbine, showing the central runner blades, the pivoting guide vanes and the surrounding volute

Figure 5.19 The 450 MW horizontal-axis Francis turbine of a small-scale plant in Scotland, commissioned in 1993. The inflow (at lower right) is 2.1 $m^3 s^{-1}$ at a head of 25 m. Part of the generator casing can be seen on the left

Limits to the Francis turbine

The available head is an important factor in selecting the best turbine for a particular site. If the head is low a large volume flow is needed for a given power. But a low head also means a low water speed, and these two factors together mean that a much larger input area is required. Attempts to increase this area whilst adapting the blades to the reduced water speed and at the same time deflecting the large volume into the draft tube led to turbines with wide entry and blades which were increasingly twisted. Ultimately the whole thing began to look remarkably like a propeller in a tube, and this is indeed the type of turbine now commonly used in low-head situations (see below).

High heads bring problems too, because they mean high water speeds. As mentioned above, Francis turbines are most efficient when the blades are moving nearly as fast as the water, so high heads imply high speeds of rotation. A look at Tables 5.1 and 5.2 in Section 5.2 reveals that the turbine at Glenlee, with its much higher head, rotates at up to twice the speed of the other Francis turbines in the Galloway system. For sites with very high heads, the Francis turbine becomes unsuitable, and yet another type takes over, as we shall see.

‘Propellers’

In the ‘propeller’ or **axial-flow** turbines shown in Figures 5.17 and 5.21, the area through which the water enters is as large as it can be: it is the entire area swept by the blades (these turbines are, again, reaction turbines). Axial-flow turbines are therefore suitable for very large volume flows and have become usual where the head is only a few metres. They have the advantage over radial-flow turbines in that it is technically simpler to improve the efficiency by varying the angle of the blades when the power demand changes. Axial-flow turbines with this feature are called **Kaplan turbines**.

An important feature of ‘propeller’ turbines is that their optimum blade speed for maximum efficiency is appreciably greater than the water speed – as much as twice as fast. This allows the high rate of rotation needed by the generator even with relatively low water speeds. (Note that because the outer parts of the blade move faster than the more central parts, the blade angle needs to increase with distance from the axis. This is why a propeller has its familiar twisted shape.)

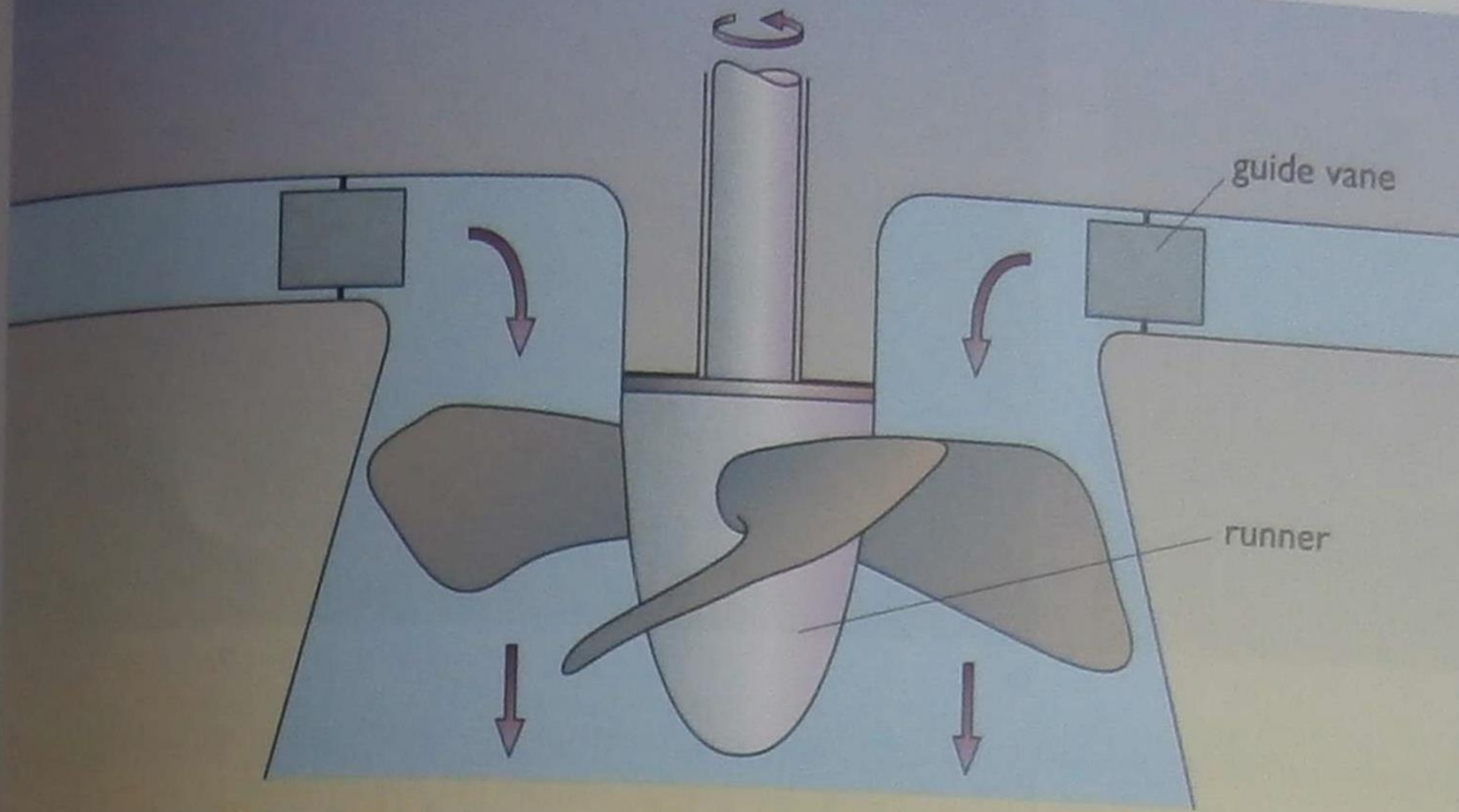


Figure 5.21 A 'propeller' or axial-flow turbine

With axial flow there is no need to feed the water in from the side, and it is obviously simpler to let it flow in along the axis instead of being deflected through a right angle. However, this raises the problem of where to position the generator: if located directly along the axis of the turbine it will either get in the way and/or get wet! Several different solutions to this problem – rim generators and tubular turbines – are shown in Chapter 6.

Pelton wheels

For sites of the type shown in Figure 5.13(c), with heads above 300 metres or so (or lower for small-scale systems) the **Pelton wheel** is the preferred turbine. It evolved during the gold rush days of late nineteenth century California, was patented by Lester Pelton in 1880, and is entirely different from the types described above. It is, in contrast to the reaction turbines discussed previously, an **impulse turbine**. One important difference between the turbine types is that whereas a reaction turbine runs fully submerged and with a pressure difference across the runner, impulse turbines essentially operate in air at normal atmospheric pressure.

A Pelton wheel is basically a wheel with a set of double cups or 'buckets' mounted around the rim (Figures 5.22 and 5.23(a)). A high-speed jet of water, formed under the pressure of the high head, hits the splitting edge between each pair of cups in turn as the wheel spins (Figure 5.23(b)). The water passes round the curved bowls, and under optimum conditions gives up almost all its kinetic energy. The power can be varied by adjusting the jet size to change the volume flow rate, or by deflecting the entire jet away from the wheel.

The efficiency of a Pelton wheel is greatest when the speed of the cups is half the speed of the water jet (Box 5.7). As the cup speed depends on the rate of rotation and the wheel diameter, and the water speed depends on the head, there is an optimum relationship between these three factors.

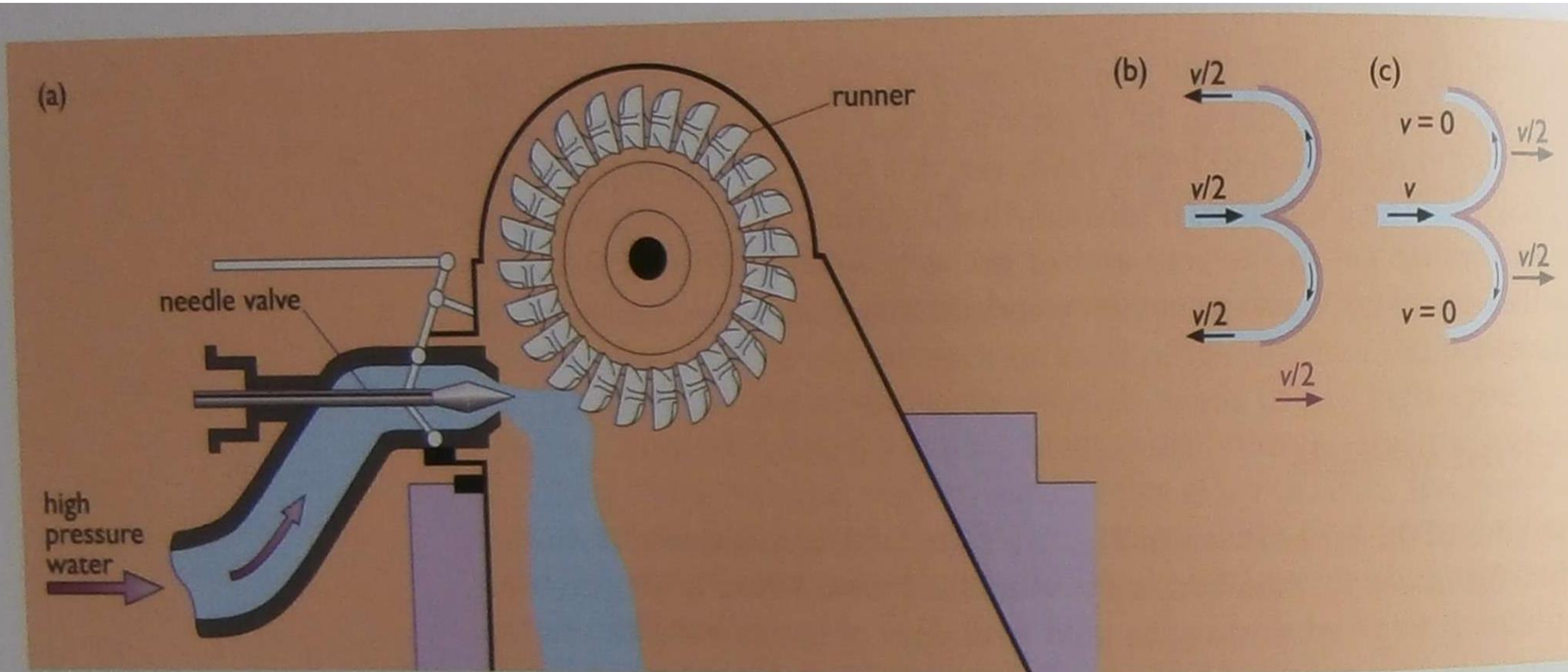


Figure 5.23 Structure of a Pelton wheel turbine: (a) vertical section, (b) water flow as seen from moving cup, (c) actual motion of water and cup

(a) (b)

Figure 5.22 The 16.5 MW Finlarig power station, on the shores of Loch Tay, draws its water from Lochan na Lairige at a head of 415 metres. Its average annual output is 70 GWh (SSE, 2011) (a) the power station, (b) the original twin-jet Pelton wheels and rotor of the horizontal-axis 30 MW multi-pole generator

Input power

The power input to a Pelton wheel is determined, as usual, by the effective head and the flow rate of the water. Box 5.8 shows that, ideally, the volume rate of flow (Q) corresponding to an effective head H is:

$$Q = A \times \sqrt{(2gH)}$$

where A is the area of the jet.

Equation (2) in Section 5.5 shows that the input power to a turbine is:

$$P = 1000 \times Q \times g \times H$$

so substituting for Q we find that:

$$P = 1000 \times A \times \sqrt{(2gH)} \times g \times H$$

Using the approximate value of g (10 m s^{-2}), the power in kilowatts becomes

$$P\,(\mathrm{kW}) = 45A\sqrt{(H^3)}$$

If adjacent cups are not to interfere with the flow, the wheel diameter needs to be about ten times the diameter of the jet. But two or even four jets can be spaced around the wheel to give greater output without increasing the size. If the number of jets is j, the power equation becomes

$$P\,(\mathrm{kW}) = 45jA\sqrt{(H^3)}$$

BOX 5.8 Effective head, water speed and flow rate

Although there are in practice always energy losses in forming a jet, we'll assume here that the water leaves the jet at the speed that it would have gained in 'free fall' through the effective head.

We know from Equation (1) in Section 5.5 that the potential energy lost by M kg of water in falling through H metres is given by:

$$\text{potential energy} = MgH$$

In Chapter 1 we saw that the kinetic energy of a moving object is proportional to its mass and the square of its speed:

$$\text{kinetic energy} = \frac{1}{2}Mv^2$$

So if all the lost potential energy is converted into kinetic energy, we have:

$$\frac{1}{2}Mv^2 = MgH$$

so $v^2 = 2gH$ and

$$v = \sqrt{(2gH)} \qquad (5)$$

If this water flows as a jet with a circular area of A square metres, the *volume* flowing out in each second (Q) will be equal to A times v. So the volume flow rate for an effective head H is given by

$$Q = A \times \sqrt{(2gH)}$$

Table 5.6 Summary of arguments for and against the dam

Issue	Criticism	Defense
Cost	The dam will far exceed the official cost estimate, and the investment will be unrecoverable as cheaper power sources become available and lure away ratepayers.	The dam is within budget, and updating the transmission grid will increase demand for its electricity and allow the dam to pay for itself.
Resettlement	Relocated people are worse off than before and their human rights are being violated.	15 million people downstream will be better off due to electricity and flood control.
Environment	Water pollution and deforestation will increase, the coastline will be eroded and the altered ecosystem will further endanger many species.	Hydroelectric power is cleaner than coal burning and safer than nuclear plants, and steps will be taken to protect the environment.
Local culture and natural beauty	The reservoir will flood many historical sites and ruin the legendary scenery of the gorges and the local tourism industry.	Many historical relics are being moved, and the scenery will not change that much.

(Table continues over page.)

Capital costs

Hydroelectricity is well-established, and much of the information listed above is easily available. The water-control systems, turbo-generators and output controls are standard items, covering a power range from a few hundred watts to hundreds of megawatts. The expected lifetime of the machinery is 25–50 years, and of the external structures, 50–100 years. Nevertheless, as mentioned in Section 5.3, it is difficult to generalize meaningfully about 'the cost of hydroelectric power', or to assess the economic potential for hydroelectricity in a country or a region.

The difficulty lies in the combination of the extremely site-specific construction costs and the heavy 'front-end loading' of these costs. In other words, the dominant factor in determining the cost per unit of hydro output is the initial capital cost, and a major part of this can be the civil engineering costs, which vary greatly from site to site.

Unit costs

An interesting study of hydro potential in the USA (Hall et al., 2003) assessed the costs for over two thousand sites with potential hydro capacities in the range 1–1300 MW. About half of these were green-field (blue-water?) sites, with no existing dams or hydro plants, and the estimated development costs for these, based on data for similar existing plants, fell mainly in the range \$2000–\$4000 per kW. (At the time of writing inflation would have increased these initial costs to about \$2400–\$4800 or approximately £1500–£3000 per kW.)

These studies revealed the striking influence of the *initial costs* in determining the cost per kilowatt-hour of output averaged over the life of a hydro plant.

4.1 Introduction

Bioenergy is the general term for energy derived from materials such as wood, straw, oilseeds or animal wastes which are, or were recently, living matter, referred to collectively as **biomass**. Wood pellets, charcoal, bioethanol and biodiesel are all examples of energy-rich materials derived from biomass.

In nature, the energy that has been stored in the biomass of plants is dissipated through a series of conversions. These involve **metabolic** processes such as **respiration** (effectively the reverse of photosynthesis) in living matter, and physical processes such as re-radiation of heat energy and the **evaporation** of water (Figure 4.1). These transfer energy to the surrounding atmosphere and eventually the energy is radiated away from the Earth as low-temperature heat. Some biomass will be metabolized within a year, but it can also accumulate over decades in the wood of trees and as the **humus** component of the soil organic matter. A small fraction may accumulate over centuries as **peat**, traditionally burned for heating, and over millions of years a tiny proportion has become the major fossil fuels: coal, oil and gas.

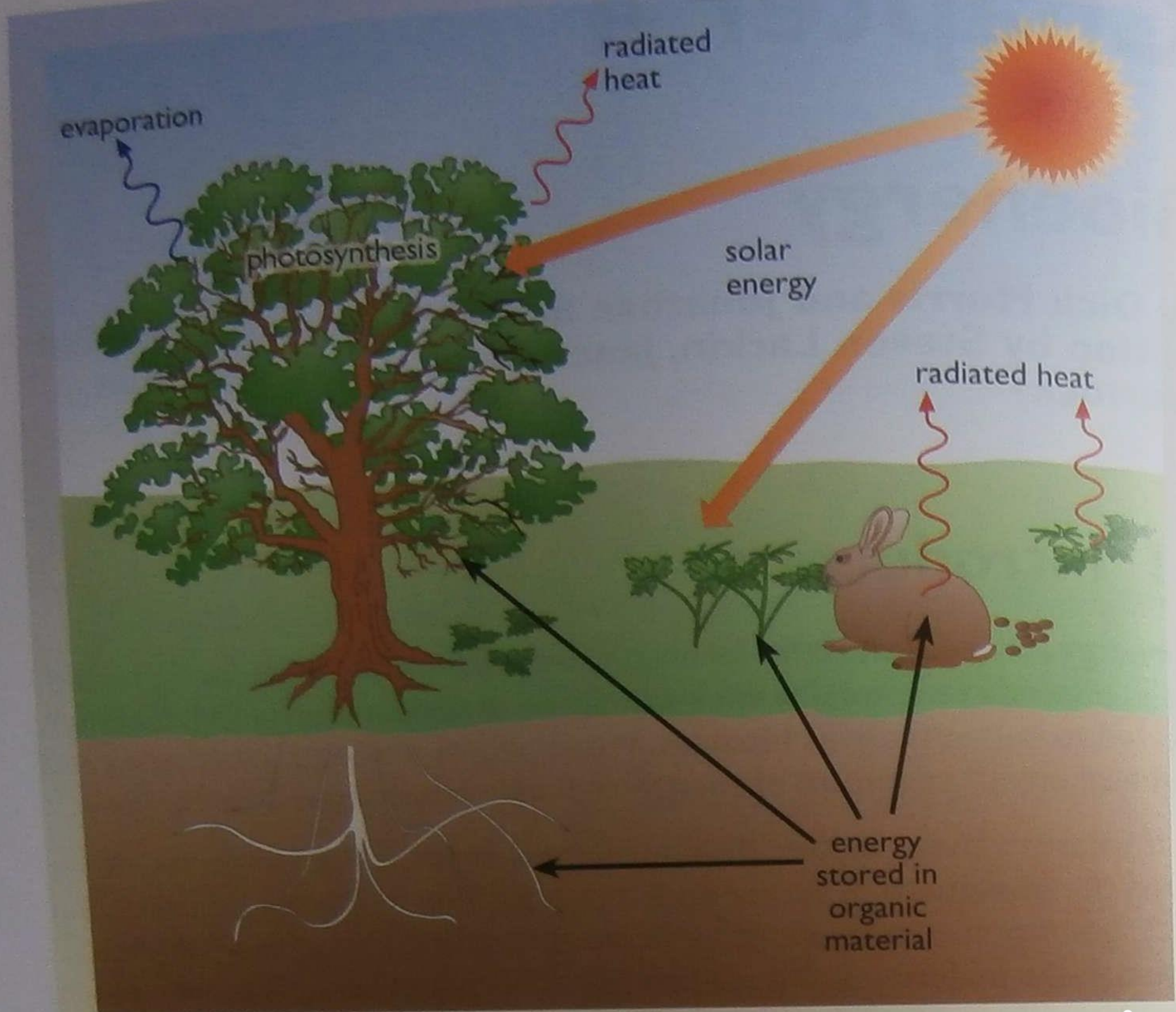


Figure 4.1 The bioenergy cycle on a local scale. In addition, a small fraction of the carbon from decomposing animal and plant residues (including roots) is transformed into soil organic matter, a significant carbon store.

4.3 Biomass as a solar energy store

The key mechanism in the use of bioenergy is photosynthesis, in which plants take in carbon dioxide and water from their surroundings and use energy from sunlight to convert these substances into plant biomass.

The essential features of the process can be represented by the chemical equation:

$$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

The first product on the right of the equation is glucose ($C_6H_{12}O_6$), a **carbohydrate** (see Box 4.2). The second product in the equation is oxygen which is released to the atmosphere. Although glucose is not necessarily the final 'vegetable matter' it is the crucial building block in subsequent biomass producing reactions. Thus a plant *grows* by using solar energy to convert carbon dioxide and water into carbohydrate or similar material, with a release of oxygen into the atmosphere.

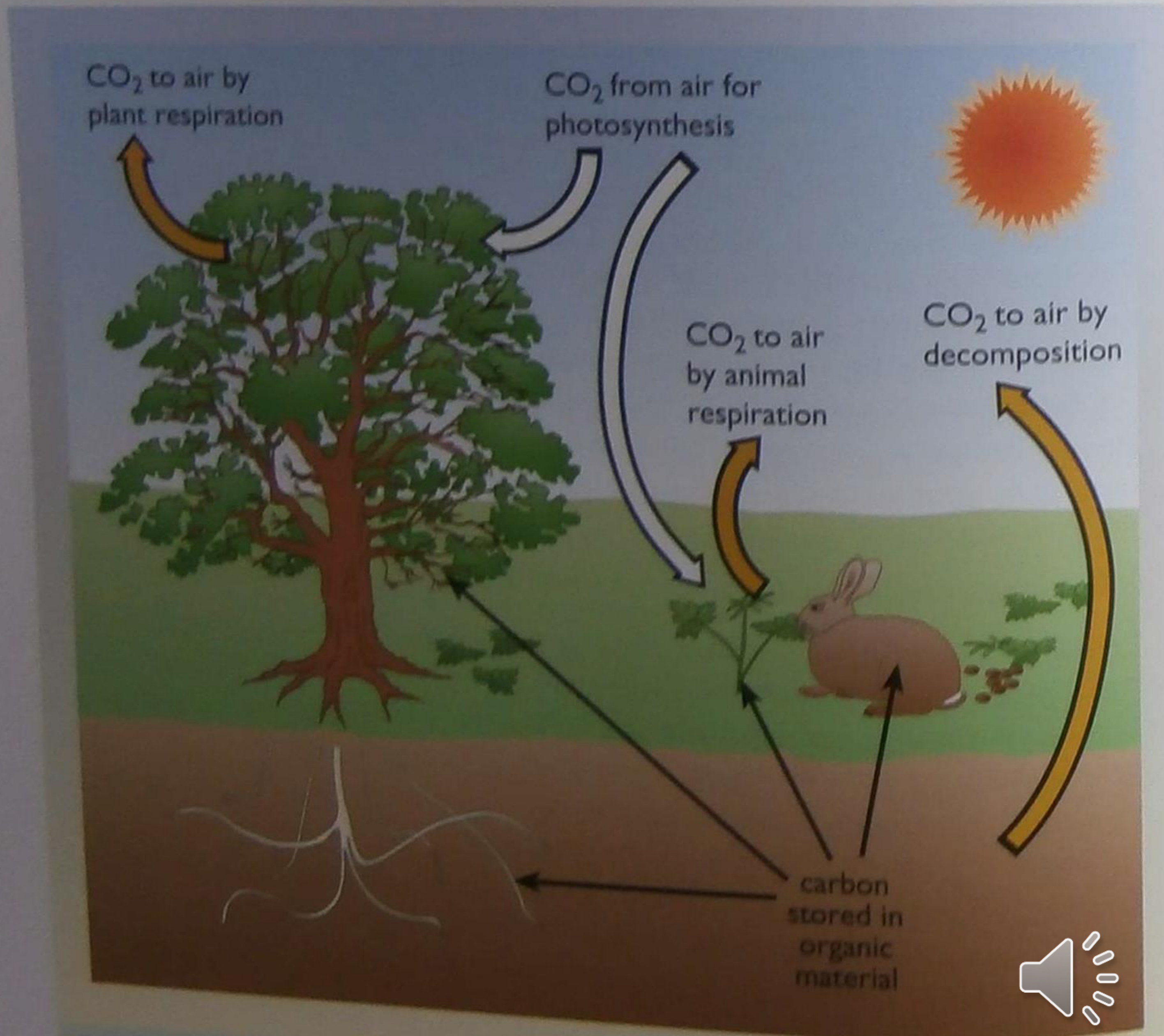


Figure 4.2 The carbon cycle on a local scale

4.4 Biomass as a fuel

What are fuels?

Fuels are those materials from which useful energy can be extracted. In using biomass as fuel, this release of energy usually involves burning (combustion). Some essential features of combustion are:

- it needs air – or to be more precise, oxygen
- the fuel undergoes a major change of chemical composition
- heat is produced, i.e. energy is released.

Consider, as an example, methane – the principal component of the fossil fuel natural gas and also one form of gaseous biofuel. Each methane molecule consists of one carbon and four hydrogen atoms: CH_4. Atmospheric oxygen has molecules consisting of two atoms (O_2), so in full combustion each methane molecule reacts with two oxygen molecules:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{energy}.$$

BOX 4.4 CO_2 from fuel combustion

As an example, consider the combustion of methane (CH_4). The masses of the atoms of carbon and oxygen are respectively 12 times and 16 times the mass of a hydrogen atom, so we can associate masses with the items in the combustion equation:

$$\begin{array}{ccccccc} CH_4 & + & 2O_2 & \rightarrow & CO_2 & + & 2H_2O \\ 12+(4\times 1) & + & 2\times(2\times 16) & \rightarrow & 12+(2\times 16) & + & 2\times(2\times 1+16) \end{array}$$

We can see, therefore, that burning 16 tonnes of CH_4 releases 44 tonnes of CO_2.

The energy content of methane is 55 GJ t^{-1} if the water vapour produced is condensed but only 50 GJ t^{-1} if it isn't (see Box 4.5). This is the amount of heat produced by burning one tonne of methane and thus releasing 2.75 tonnes (2750 kg) of CO_2.

Other fossil fuels, apart from coal, are chemically more complex than methane (although many are hydrocarbons like methane in that they consist almost entirely of hydrogen and carbon), but their combustion follows a similar process. The heat produced per tonne is rather less, however, and they also produce more CO_2 per tonne because they have a higher ratio of carbon to hydrogen atoms, so the CO_2 per unit of heat output is greater (see Table 4.1). Coal, which is largely carbon, produces one of the highest outputs of CO_2 per unit of heat output. Coal and oil may also contain sulfur which burns to sulfur dioxide. This sulfur can be refined out or collected from flue gases and used in fertilizers.

Table 4.1 Heat content (net calorific value, see Box 4.5) and CO_2 emissions

Fuel	Heat content/GJ t^{-1}	CO_2 released/kg GJ^{-1}
Coal	24	94
Fuel oil	41	79
Natural gas	48	57
Air-dry wood	~15	~80*

Note that the composition of coal, oil and wood and the moisture content can vary significantly, so the figures are typical values.

* If the wood is grown sustainably, so that trees are planted to replace those harvested and combustion is complete, its *life cycle* CO_2 emission should be close to zero.

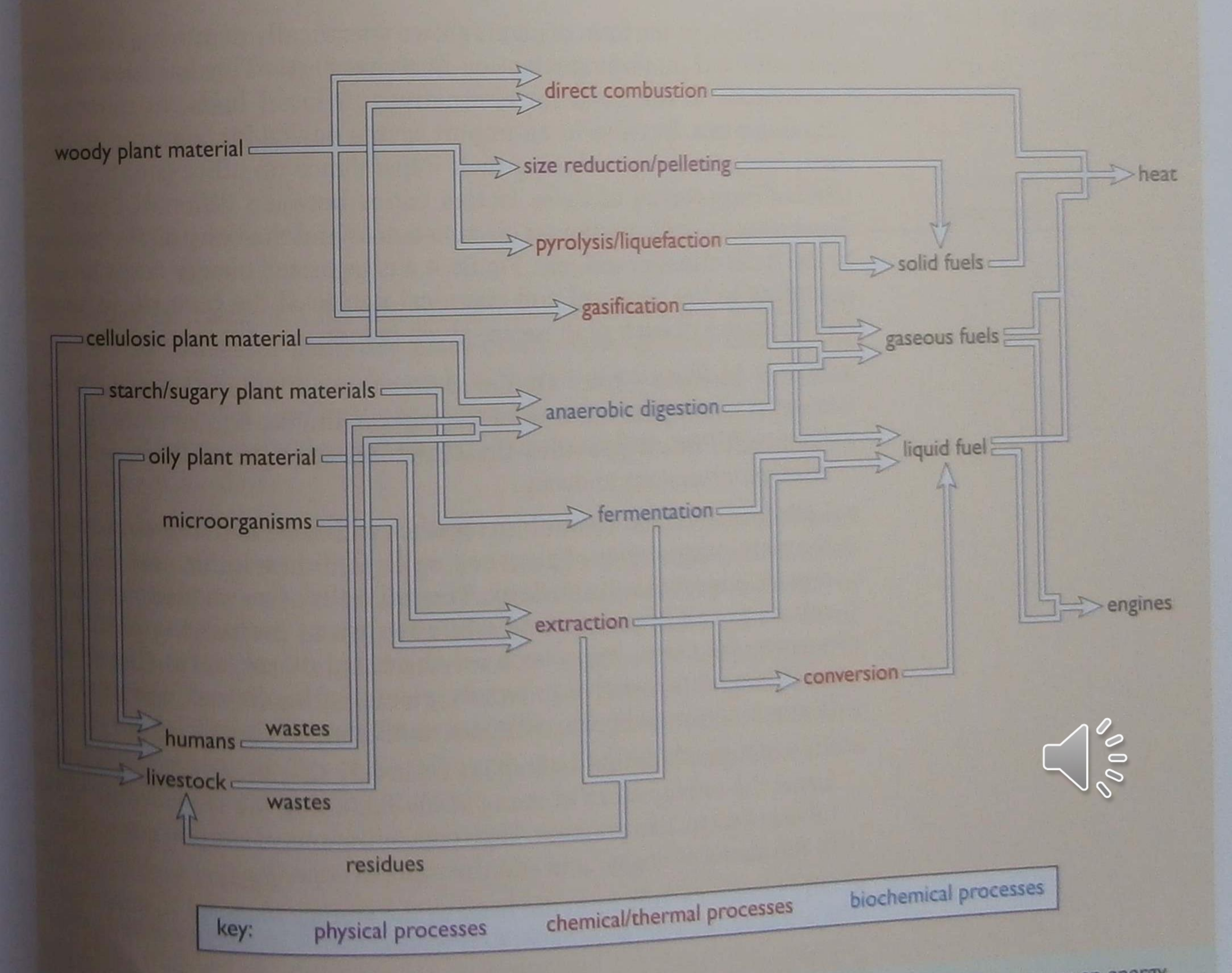
Sources: DECC, 2011, AEA, 2011.

Table 4.2 Typical heat energy content (net calorific value, see Box 4.5) per unit of dry mass and volume of various forms of biomass and fossil fuel

Fuel	Energy content	
	$GJ\ t^{-1}$	$GJ\ m^{-3}$
Wood (green, 60% moisture)	6	7
Wood (air-dried, 20% moisture)	15	9
Wood (oven-dried, 0% moisture)	18	9
Charcoal	30	*
Paper (stacked newspapers)	17	9
Dung (dried)	16	4
Grass (fresh-cut)	4	3
Maize grain (air-dried)	19	14
Straw (as harvested, baled)	15	1.5
Sugar cane residues (bagasse)	17	10
Domestic refuse (as collected)	9	1.5
Commercial wastes (UK average)	16	*
Domestic heating oil	43	36
Coal (domestic heating, average)	28	50
Natural gas (at supply pressure)	48	0.04

* Indicates dependence on specific types of material.

Source: includes data from Biomass Energy Centre, 2011a.

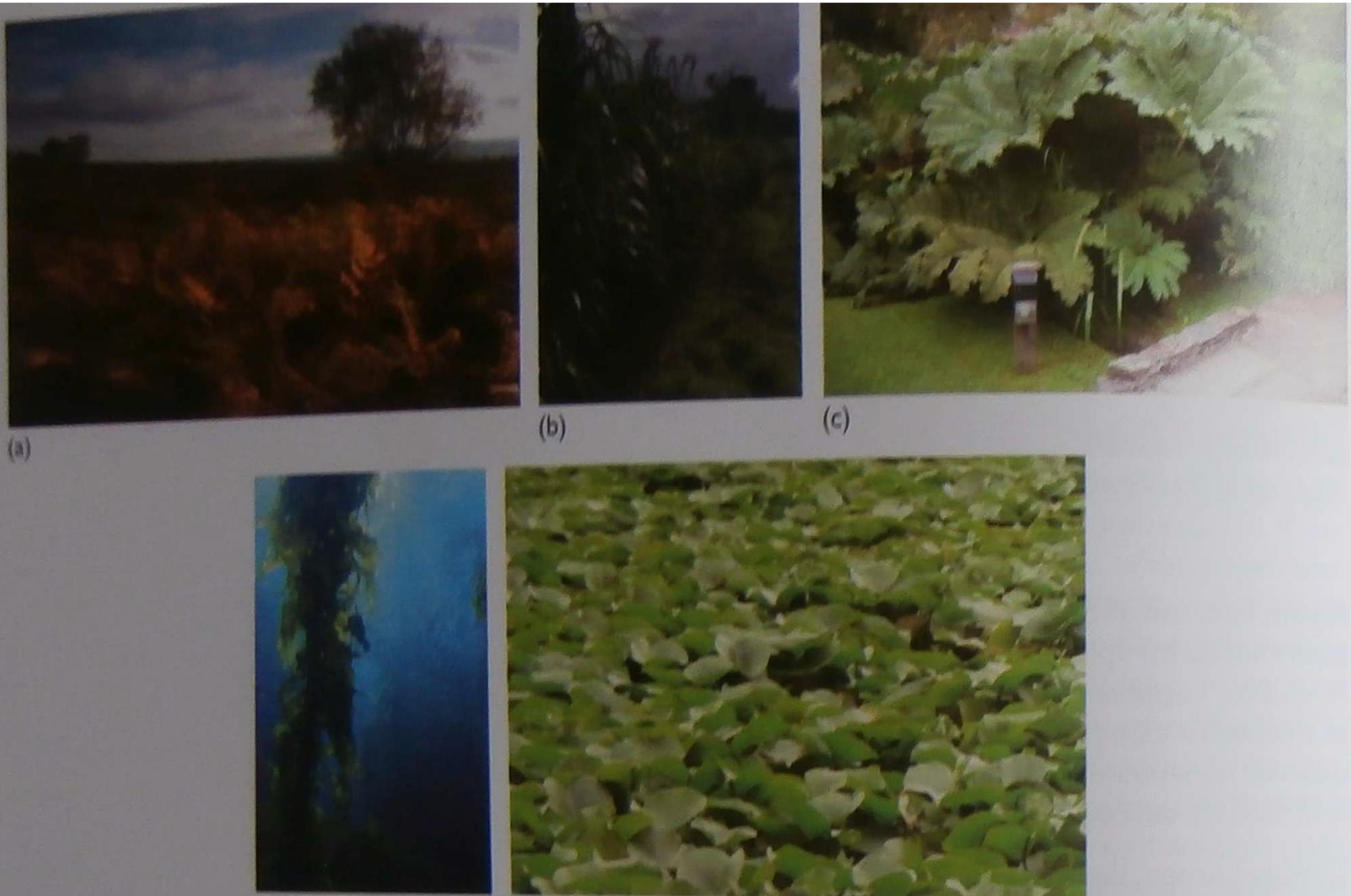

direct combustion
woody plant material
size reduction/pelleting
heat
pyrolysis/liquefaction
solid fuels
gasification
cellulosic plant material
gaseous fuels
starch/sugary plant materials
anaerobic digestion
oily plant material
liquid fuel
microorganisms
fermentation
engines
extraction
conversion
humans
wastes
livestock
wastes
residues
key:
physical processes
chemical/thermal processes
biochemical processes

- Woody biomass – trees are the main source of woody biomass. Wood itself is a complex mixture of the carbohydrates, lignin, cellulose and hemicellulose. It provides the structural strength of the tree and is relatively resistant to decay.
- Cellulosic biomass – cellulose together with related hemicelluloses are the main components of plant cell walls. Cellulose is the most abundant organic large molecule on Earth. The cell walls of seaweeds are primarily cellulose and hemicellulose while terrestrial herbaceous plants like grasses, the cereal crops such as wheat and maize (corn) also contain small amounts (relative to woody plants) of lignin and lignocellulose (a combination of lignin, cellulose and hemicellulose).
- Starch/sugary biomass – starch is a relatively simple carbohydrate which forms the energy store in many seeds including the cereals and in the tubers of crops like potatoes. High concentrations of simpler sugars occur in the stems of sugar cane and the roots of sugar beet.
- Oily biomass – oils form the basis of the storage material in some seeds such as oilseed rape, soya and oil palms.
- Microorganisms – a possible novel 'energy crop' is represented by microalgae, which can have high concentrations of oils in their cells.

This general catego

Table 4.3 A broad generalized classification of primary bioenergy sources

Category	Major energy-rich components	Structural strength /resistance to natural decay	Examples	Typical yields of dry matter /t ha^{-1} y^{-1}
Woody biomass	Lignin/lignocellulose (complex carbohydrates)	High	Trees (deciduous or hardwoods)	10 (temperate) to 20 (tropics)
Cellulosic biomass	Cellulose/lignocellulose (complex carbohydrates)	Medium	Grasses (e.g miscanthus), water hyacinth, seaweeds	10 (temperate) to 60 (tropical aquatics)
Starch/sugar crops	Simpler carbohydrates	Low	Cereals (maize, sugar cane, wheat)	10 (temperate cereals) to 35 (sugar-cane)
Oily crops	Lipids (i.e. oils/fats)	Low	Oilseeds (rape, sunflower, oil palm, jatropha)	8 to 15
Microorganisms	Oils	Low	Microalgae	Unknown – still speculative



(a) (b) (c) (d) (e)

Figure 4.6 Some possible plants for production of cellulosic biomass: (a) bracken, (b) miscanthus, (c) *Gunnera*, (d) kelp, (e) water

Figure 4.7 Harvesting miscanthus using conventional agricultural machinery

(a) (b) (c)

Figure 4.8 Starch/sugar crops: (a) sugar cane, (b) maize harvesting, (c) sugar beet

Extraction of oils

The oil in crops such as rapeseed, soya and oil palms is contained within the seed, which also contains the plant embryo and may have a structural shell or coat for protection. The oil has to be separated from these surrounding tissues, either by pressing or by using a **solvent** which dissolves the oil making it less viscous and easier to separate from the remaining material. Commercial oilseed extraction involves a number of steps including:

- seed cleaning – removal of foreign matter
- tempering – pre-heating of the seed to improve ease of oil extraction
- dehulling – removal of seed coat
- flaking – to increase surface area
- conditioning – re-heating the flaked seed
- mechanical extraction – by pressing and extrusion and/or expansion
- solvent extraction – for maximum extraction of oil.

A typical press for the mechanical extraction stage uses a metal screw to force the material over a sieve, which allows the oil to pass out but retains the fibrous material for separate ejection (Figure 4.15).

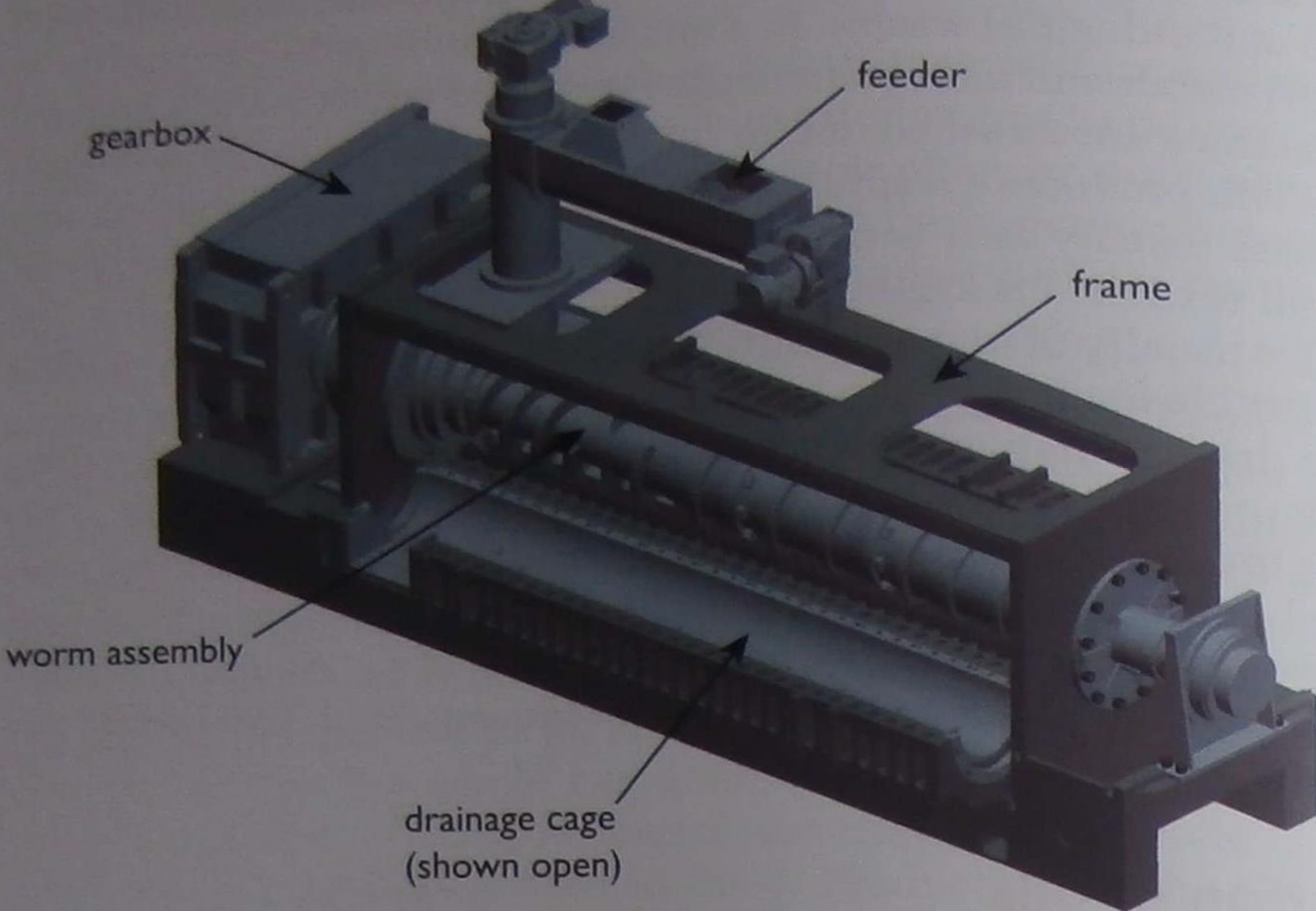


Figure 4.15 Schematic of a screw press for oilseed extraction

4.8 Thermochemical processing

Themochemical processing involves the use of heat (thermo-) and possibly the use of chemical reagents, to convert biomass into energetically more useful forms. The output from such processes may be heat, or intermediate gaseous or liquid fuels.

Combustion of solid biomass

Most biomass is initially solid, and can be burned in this form to produce heat for use *in situ* or in close proximity, although it may first require relatively simple physical processing, sorting, chipping, compressing and/or air-drying, as discussed above.

Direct combustion is a simple process to release useful energy. Unfortunately, it can be very inefficient (as exemplified in Box 4.8) and can potentially produce a wide range of pollutants.

BOX 4.8 Boiling a litre of water over a wood fire

How much wood is needed to bring one litre of water to the boil?

The starting point for answering this question is to apply the following equation:

$$\text{Heat energy required} = \text{mass} \times \text{temperature rise} \times \text{specific heat capacity of water}$$

Note: the **specific heat capacity** (sometimes called the specific heat) of a substance is the amount of energy in joules that has to be transferred to 1 kg of material to raise its temperature by 1 kelvin.

Data

Specific heat of water	$= 4200\ \text{J kg}^{-1}\ \text{K}^{-1}$
Mass of 1 litre of water	$= 1\ \text{kg}$
Heat value of air-dry wood (Table 4.1)	$= 15\ \text{MJ kg}^{-1}$
Density of air-dry wood	$= 600\ \text{kg m}^{-3}$
1 cubic centimetre ($1\ \text{cm}^3$)	$= 10^{-6}\ \text{m}^3$

Calculation

Heat energy needed to heat 1 litre of water from 20 °C to 100 °C $= 80 \times 4200$ J

$= 336$ kJ

Heat energy released in burning 1 cm^3 of wood $= 15 \times 600 \times 10^{-6}$ MJ

$= 9.0$ kJ

Volume of wood required $= 336 \div 9.0\ cm^3$

$= 37\ cm^3$. (say, two 200 mm sticks)

Experience suggests that on an open fire many more than two thin 200 mm sticks would be needed. However, a well-designed enclosed stove using small pieces of wood could boil the water with as little as four times this 'input' – implying an efficiency of 25%.

Pyrolysis and gasification

These related processes involve heating biomass materials in such a way that they decompose to produce useful products, without complete combustion. **Pyrolysis** is the simplest and almost certainly the oldest method of processing one fuel in order to produce a better fuel, in the form of charcoal. Other, more controlled forms of pyrolysis, and similar techniques of gasification, have since been developed to produce solid, gaseous and liquid biofuels.

of air. A complete industrial gasification process using oxygen can produce a stream of carbon monoxide and hydrogen, with any other impurities such as tars, ammonia and sulfur compounds being chemically removed. This is known as **synthesis gas**, or **syngas**.

From syngas, almost any hydrocarbon compound may be synthesized, including premium liquid fuels such as methanol. The first stage in the synthesis is to adjust the proportions of H_2 and CO to the ratio required in the desired product. For example, methanol is CH_3OH, and therefore needs two H_2 molecules for each CO converted.

BOX 4.9 Power station turbine systems

Most of the world's power stations use the heat from burning fuel to produce hot, high-pressure steam for the **steam turbines** that drive the generators (Figure 4.16). Steam temperatures are limited to about 600 °C for technical reasons, so the maximum Carnot efficiency is about 65%, and the actual efficiency perhaps 45% (see Box 2.4 in Chapter 2).

Gas turbines, driven directly by the combustion products of a burning gas at 1000 °C or more, should have higher efficiencies, but the most significant improvement is achieved in the **combined cycle gas turbine** (CCGT) system. The gases leaving the gas turbine are still hot enough to raise steam for a secondary, steam turbine. In order not to corrode or foul the gas turbine blades, the fuel burned must be very clean. Nearly all present gas turbine and CCGT plants burn natural gas or vaporized light heating oil.