4.6 Combustion of solid biomass

We now turn from the biomass sources to the ways in which they are used or might be used. If biofuels are to compete with our present fuels, they must be able to meet the demand for appropriate forms of energy at competitive prices. Two important criteria are the *availability* and the '*transportability*' of the supply. The premium fuels – oil and natural gas – are valued because their energy can be stored with little loss and made available where and when we need it. The biomass resource comes in a variety of forms, as we have seen. Many are relatively high in water content and decompose rather quickly, so few are good long-term energy stores. Relatively low energy densities mean that they are also likely to be bulky and expensive to transport over appreciable distances. Recent years have therefore seen considerable research effort devoted to means for converting biomass into more convenient forms of energy.

Most biomass is initially solid, and it can be burnt in this form to produce heat for use *in situ* or at not too great a distance. It may first require relatively simple *physical* processing, involving sorting, chipping, compressing and/or air-drying. These uses are discussed in this section. Alternatively, the biomass can be upgraded by *chemical* or *biological* processes to produce gaseous or liquid fuels. These options are discussed in Sections 4.7 and 4.8.

Combustion of wood and crop residues

Boiling a pan of water over a wood fire is a simple process. Unfortunately, it is also very inefficient, as Box 4.7 reveals.

BOX 4.7 Boiling a litre of water

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

Data

Specific heat capacity of water = 4200 J kg^{-1} K^{-1}

Mass of 1 litre of water = 1 kg

Heat value of wood (Figure 5.13) = 15 MJ kg^{-1}

Density of wood = 600 kg m^{-3}

1 cubic centimetre (1 cm^3 = 10^{-6} m^3

Calculation

Heat energy needed to heat 1 litre of water from 20 °C to 100 °C = 80 × 4200 J = 336 kJ

Heat energy released in burning 1 cm^3 of wood = 15 × 600 × 10^{-6} MJ = 9.0 kJ

Volume of wood required = 336 ÷ 9.0 = **37 cm^3**.

Experience suggests that on an open fire much more than two thin 20 cm sticks would be needed. But a well-designed stove using small pieces of wood could boil the water with as little as four times this 'input' – an efficiency of 25%

Designing a stove or boiler that will make good use of valuable fuel requires an understanding of the series of processes involved in combustion. The first process, which consumes rather than produces energy, is the evaporation of any water in the fuel (see Box 4.3). Then, in the combustion process itself, there are always two stages, because any solid fuel contains two combustible constituents. The **volatile matter** is released as a mixture of vapours as the temperature of the fuel rises. The combustion of these produces the little spurts of flame seen around burning wood or coal. The solid which remains consists of the **char** together with any inert matter. The char, mainly carbon, burns to produce CO_2, whilst the inert matter becomes clinker, slag or ashes.

A feature of the biofuels is that three-quarters or more of their energy is in the volatile matter (unlike coal, where the fraction is usually less than half). The design of any stove, furnace or boiler should ensure that these vapours burn, and don't just disappear up the chimney. Air must also reach all the solid char, which is best achieved by burning the fuel in small particles. This can raise a problem, because finely divided fuel means finely divided ash – particulates that must be removed from the flue gases. The air flow should also be controlled: too little oxygen means incomplete combustion and leads to the production of poisonous carbon monoxide. Too much air is wasteful because it carries away heat in the flue gases.

Modern systems for burning biofuels are as varied as the fuels themselves, ranging in size from small stoves through domestic space and water heating systems to large boilers producing megawatts of heat (see for instance Box 4.6).

Wood burning produces a wide range of pollutants, and the past few decades have seen many programmes in developing countries for the design and dissemination of improved stoves. With the joint aims of reducing both fuel consumption and smoke emissions inside houses, these have ranged from small scale trials to major national programmes, as in China and India. A project to introduce a locally-produced charcoal-fired stove, the jiko, in Kenya is claimed to have been particularly successful. (For more detailed accounts, see UNDP, 2000 and Anderson *et al*, 1999.)

Charcoal

Charcoal is traditionally produced in the forests where the wood is cut. The 'kiln', consisting of stacked wood covered with an earth layer, is allowed to smoulder for a few days in the near absence of air, typically at 300–500 °C, a process called *pyrolysis*. The volatile matter is driven off, leaving the charcoal (the 'char' component mentioned above). Charcoal is almost pure carbon, with about twice the energy density of the original wood and burning at a much higher temperature, so it is much easier to design a simple and efficient stove for use with this high quality fuel. However, from 4 to 10 tonnes of wood are needed for each tonne of charcoal, and if no attempt is made to collect the volatile matter, up to three-quarters of the original energy content can be lost. The process also releases vaporized tars and oils and the products of incomplete combustion into the atmosphere, making this charcoal fuel cycle probably the most greenhouse gas intensive in the world. (See Section 4.8 for modern pyrolysis methods.)

Combustion of municipal solid wastes

In many countries in continental Europe and elsewhere, refuse incineration with heat recovery, or **energy-from-waste (EfW)**, is an important means of waste disposal. The heat may be used directly for district heating, or for power production (often in CHP plant). The inert ash can be used as hardcore. Countries with successful recycling and composting programs have often seen parallel growth in EfW, which accounts for 30–60% of MSW disposal in most Western European countries. World installed capacity is over 3 GW, about half of it in Europe.

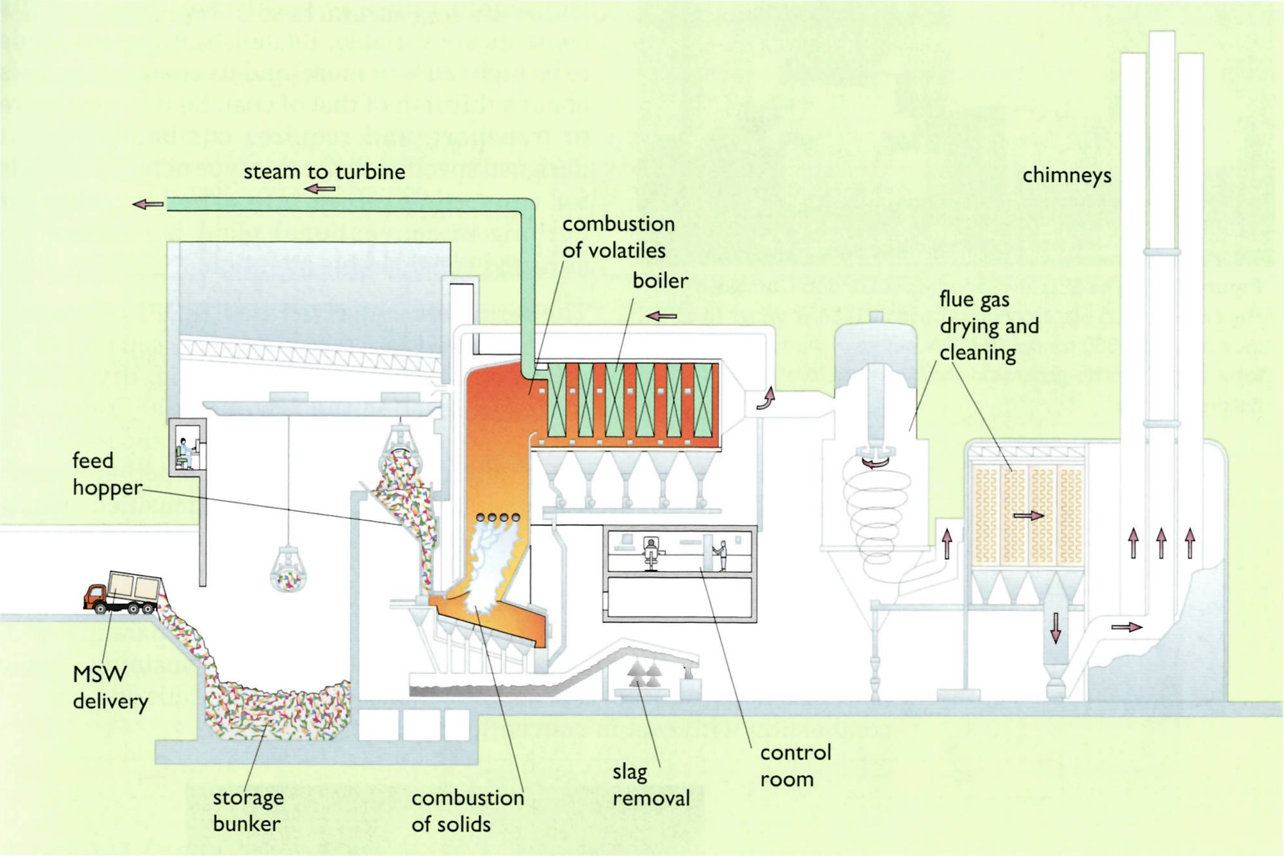

Figure 4.10 A large MSW combustion plant

EfW is becoming financially attractive in large cities in Britain because of the shortage of suitable landfill sites and the high costs of transporting wastes to distant sites (see Section 4.10). Encouraged by support under the NFFO scheme, UK capacity tripled during the 1990s, and all MSW combustion plants in the UK now make use of their heat output (see, for instance, Figure 4.11).

However, three-quarters of the UK EfW schemes proposed during the 1990s failed to obtain planning permission, mainly following public opposition. This often centred on air pollution (see Section 4.9), with further concerns about the delivery and storage of wastes. Many environmental groups are opposed to waste combustion, arguing for more waste reduction and recycling. Measures to encourage recycling and the reduction of packaging, making manufacturers responsible for the recycling of their products, could eventually lead to a reduction in the volume of MSW, but they may take years to become fully effective. Meanwhile, with ever more stringent restraints on landfill, EfW may be the only viable short-term option.

Figure 4.11 The SELCHP (South-East London Combined Heat and Power) plant, commissioned in 1984, is designed to incinerate 420 000 tonnes of MSW per year, producing steam for a 31 MW turbo-generator and heat for a local district heating scheme

Pelletted fuel

Household refuse is hardly an ideal fuel. Its contents are variable, its moisture content tends to be high (20% or more) and its energy density is about a thirtieth of that of coal. So it is expensive to transport, and requires combustion plant designed specifically for this type of fuel. Methods for converting refuse into a fuel suitable for burning in conventional plant have therefore attracted considerable attention.

The term **refuse-derived fuel** (RDF) refers to a range of products resulting from separation of unwanted components, shredding, drying and otherwise treating the raw material. Relatively simple processing might involve separation of very large items, magnetic extraction of ferrous metals and perhaps rough shredding. The most fully processed product, known as **densified refuse-derived fuel** (or d-RDF), is the result of separating out the combustible part which is then pulverized, compressed and dried to produce solid fuel pellets with perhaps twenty times the energy density of the original material (Figure 4.12). The UK has six processing plants, mechanically separating non-combustibles such as metals and glass, and pelletizing the remaining organic matter. Their reduced ash content makes the pellets suitable for co-combustion with coal in conventional plant.

Figure 4.12 Refuse-derived fuel (d-RDF) pellets

4.7 Production of gaseous fuels from biomass

There are several reasons for growing interest in the production of **gaseous fuels** from biomass. The result is a more versatile fuel, suitable not only for burning but for use in internal combustion engines or gas turbines. It is easier to transport, and if undesirable pollutants and inert matter are removed during processing, it will be cleaner. It offers a route to electric power that could be more efficient than the direct combustion of biomass in a conventional power station. And finally, gasification under suitable conditions can produce **synthesis gas**, a mixture of carbon monoxide and hydrogen from which almost any hydrocarbon, synthetic petrol, or even pure hydrogen can be made.

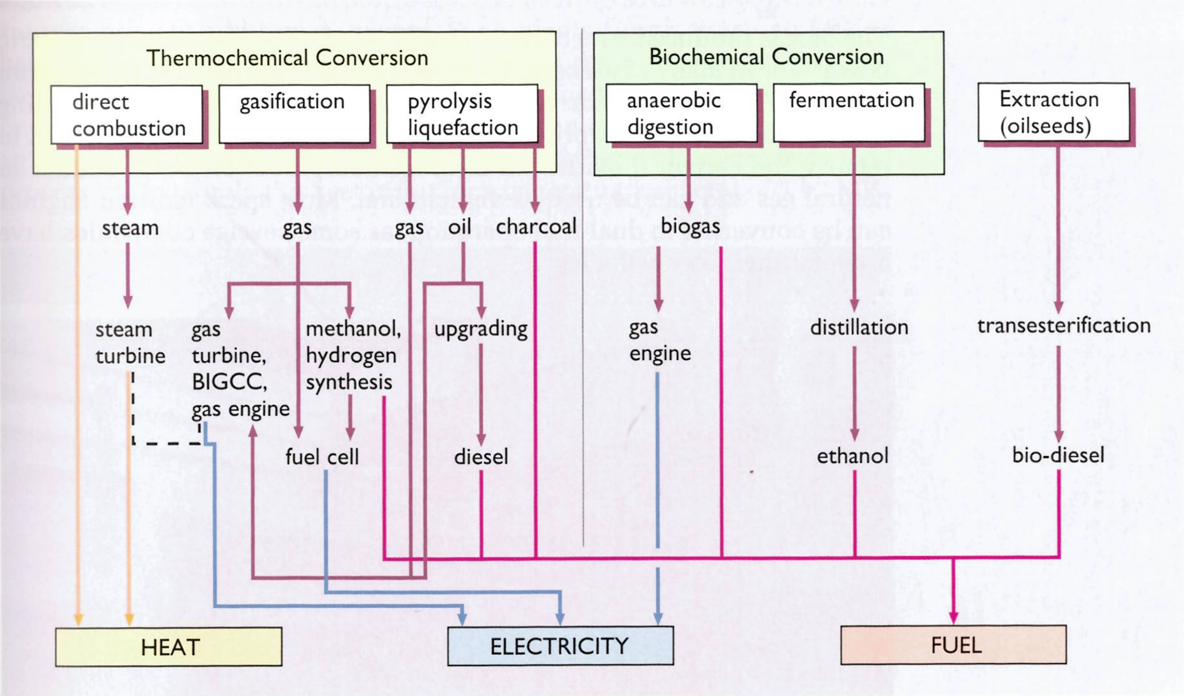

Figure 4.13 Main bioenergy conversion routes

Anaerobic digestion

We have seen two examples of anaerobic digestion of wastes: biogas and landfill gas. In the latter case, the 'digester' is the landfill itself, and the operator has only limited control of the processes. The digestion of 'wet wastes' is quite different. The feedstock, dung or sewage, is converted to a slurry with up to 95% water, and fed into a purpose-built **digester** whose temperature can be controlled. Digesters range in size from perhaps one cubic metre for a small 'household' unit (roughly 200 gallons) to some ten times this for a typical farm plant and more than 1000 m^3 for a large installation (Figure 4.15). The input may be continuous or in batches, and digestion is allowed to continue for a period of from ten days to a few weeks.

The process of anaerobic digestion is complex, but it appears that bacteria break down the organic material into sugars and then into various acids which are decomposed to produce the final gas, leaving a residue whose composition depends on the system and the original feedstock. The bacterial action itself generates heat, but in cooler climates additional heat is normally required to maintain the ideal process temperature of at least 35 °C, and this must be provided from the biogas. In extreme cases *all* the gas may be used for this purpose, but although the net energy output is then zero, the plant may still pay for itself through the saving in fossil fuel which would have been needed to process the wastes.

In a well-run digester, each dry tonne of input will produce 200–400 m^3 of biogas with 50% to 75% methane, an average energy output of perhaps 8 GJ per tonne of input. This is only about half the fuel energy of dry dung or sewage, but the process may be worthwhile in order to obtain a clean fuel and dispose of unpleasant wastes.

The biogas produced by a digester can be used to produce heat or electric power – or in many cases both. It can be used in large internal combustion engines (Figure 4.14) to drive electric generators, with the engine cooling water and exhaust gases providing heat to the digester. If it is scrubbed to remove the carbon dioxide and hydrogen sulphide, biogas is similar to natural gas and can be used as vehicle fuel. Most spark ignition engines can be converted to dual fuel operation, as some sewage companies have done for their own vehicles.

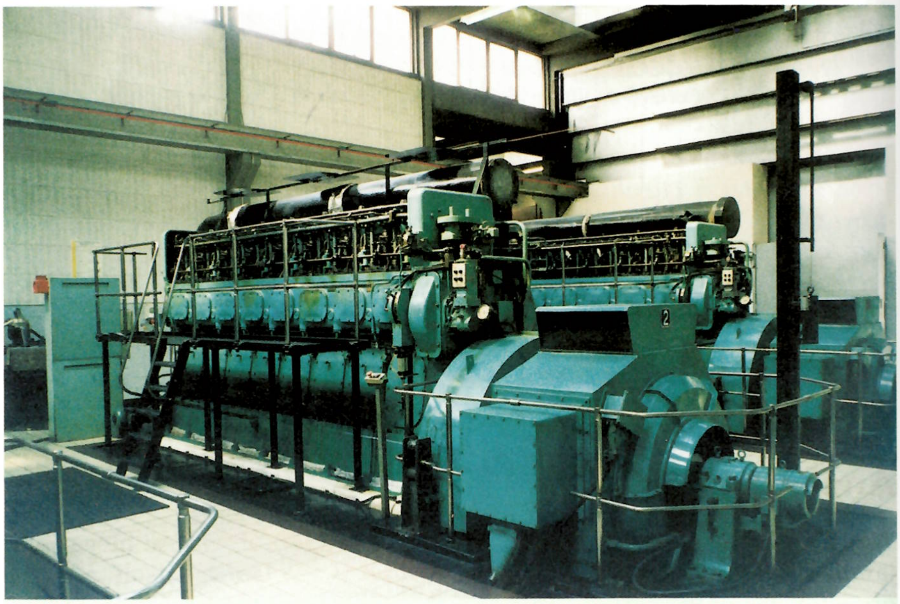

Figure 4.14 Sewage gas engine

The energy content of the annual wastes from housed animals in the UK is thought to exceed 100 PJ, and the estimated *accessible resource* in the form of biogas is about 10 PJ, enough to support an installed generating capacity of perhaps 100 MW. However, although the technology is well developed, with a range of digesters commercially available, the relatively high capital cost has tended to limit UK investment. A further disincentive has been the difficulty in maintaining the right operating conditions and blend of feedstock in small-scale plants. In the mid-1990s the total installed capacity in the UK remained under 1 MW (ETSU, 1999).

Manures from cattle, chickens and pigs are the most common wet wastes in Europe, especially in the Netherlands and Denmark, where limited land is available for the spreading of slurry. A Danish government programme investigating the economics of anaerobic digestion concluded after a six-year trial that a *large-scale* biogas plant could be profitable if three realistic conditions were met:

- the plant is operated in combined heat and power mode
- the gas is sold at a price comparable to that of natural gas
- credit is given for the disposal of other wastes

This proved to be the case. Central plants set up by farmers' co-operatives allowed better control of the processes, and dealing with wastes from other sources brought additional income. Such plants supply some 40 MW of heat output in Denmark and about 10 MW in the Netherlands. The first large-scale plant in Britain was commissioned in 2002 (Figure 4.15). Based on a design that has proved successful in Denmark and Germany, it uses an annual 146 000 t of slurry from 28 farms, together with wastes from food processors, to supply the heat input for a generating capacity of 1.43 MW.

Figure 4.15 Large-scale anaerobic digestion plant at Holsworthy in Devon

The developing world has seen many schemes for biogas plants during the past few decades. A major Chinese programme in the 1970s initially resulted in more than 7 million digesters, but suffered from many failures. A later drive, with better technology and supporting infrastructure, resulted in some 5 million domestic plants operating successfully by the mid-1990s.

In India 2.8 million biogas plants were installed by the end of 1998 and a potential for 12 million has been identified (UNDP, 2000). However, in many developing countries the capital cost of a digester is out of reach of the typical small farmer, and attempts to introduce community biogas plants have met with mixed fortunes, largely due to difficulties with balancing 'ownership' of animal dung against credit in the form of biogas consumption. As a result, many of the biogas plants in India are concentrated on wealthier farms with larger numbers of cattle.

Anaerobic digesters for MSW

As an alternative to recovery of biogas from landfills, MSW can be subjected to more carefully controlled processing in the type of large digester described above. Under these conditions gas yields are much higher and digestion is complete within a matter of weeks rather than years. Feedstock for the digester is the organic fraction of MSW diluted into a slurry – possibly mixed with sewage.

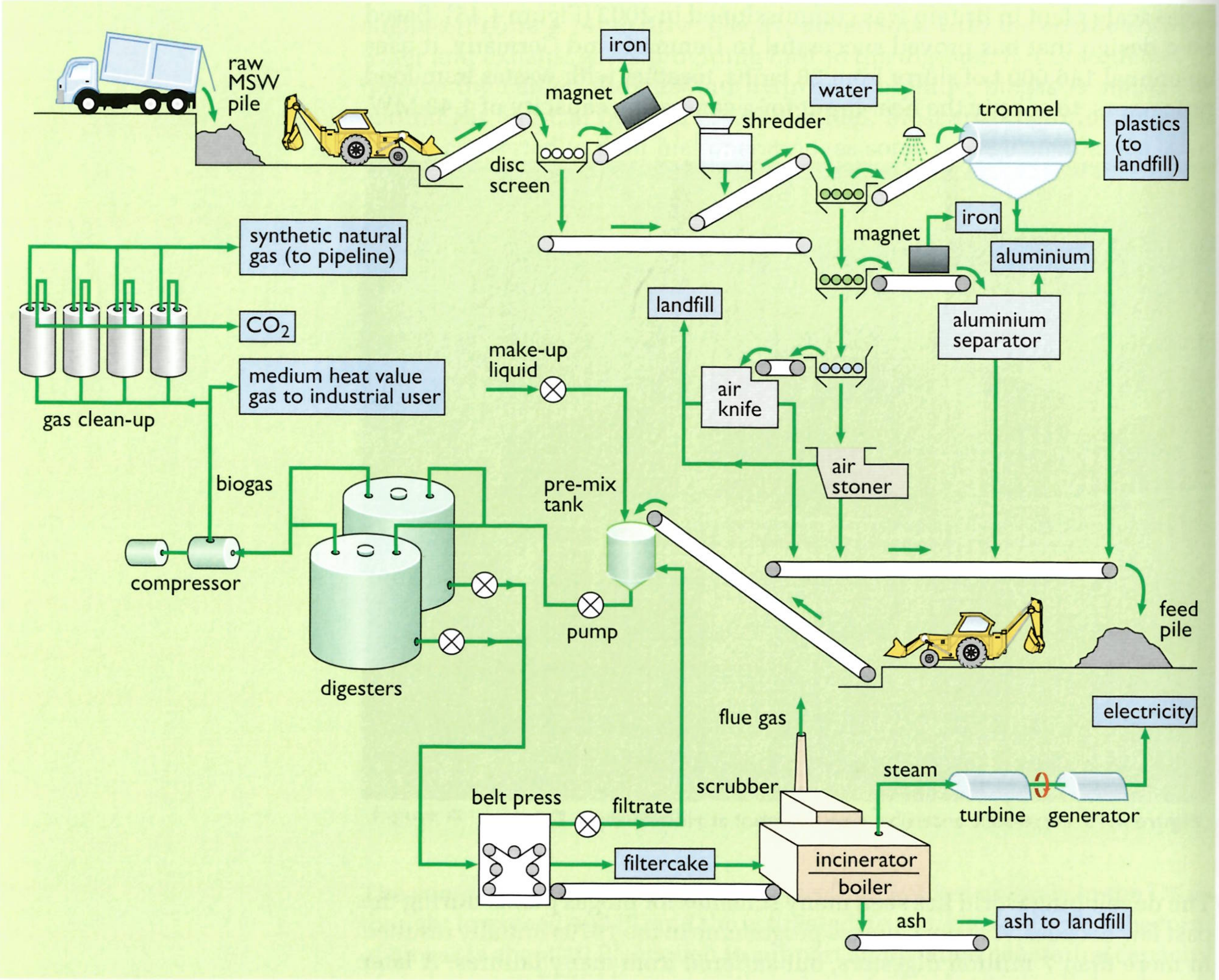

Figure 4.16 This integrated waste materials plant has facilities for recovery of metals and removal of plastics, followed by anaerobic digestion of the remainder. The solid residue from the digester serves as fuel for power production

An advantage over landfill is that these digesters can be closer to urban areas, reducing transport costs. They also require much less land. The greater capital and processing costs have, however, been a disincentive to investment. Plants already exist in several European countries, and although the UK has none yet, interest is growing due to the rising cost of landfill. Low-solids systems have been developed particularly in the USA, and Figure 4.16 shows the full complexity of a system which first recovers useful materials from the MSW, then produces methane by digestion and finally generates electric power using the combustion heat of the residual solids.

Gasification

In contrast to the mainly *biological* process of anaerobic digestion, the term **gasification** is used for *chemical* processes by which a gaseous fuel is produced from a solid fuel (see Figure 4.13 above.) Gasification is not a new process. 'Coal gas', the product of coal gasification, was widely used in the UK and elsewhere for many decades, and 'wood gas' was used for heating, lighting, and even as vehicle fuel. Both were superseded by natural gas – although wood gasifiers reappeared during the coal shortages of World War II.

There are many different designs of modern gasifier, but essentially one basic process: hot steam and oxygen interacting with the solid fuel. The gasification reactions do not occur easily, and need operating temperatures from a few hundred to over a thousand degrees Celsius, with pressures from a little above atmospheric pressure to 30 times this. The process begins with the release of the volatiles from the heated solid, leaving the char. These two components in turn undergo a reactions with steam and oxygen, resulting in **producer gas**, a mixture of combustible components (mainly carbon *monoxide* and hydrogen, with some methane, higher hydrocarbons and condensable tars) together with carbon dioxide and water. Further processing may break down some of the combustibles to give a cleaner gas. Nitrogen will also be present if air is used, rather than oxygen, and the energy content of the resulting gas is then only 3–5 MJ m^{-3}, about a tenth of that of natural gas. (Using pure oxygen gives a more valuable gas, but the additional cost of the oxygen plant makes this economic only for very large systems, and at the time of writing is used only in *coal* gasifiers.)

Small gasification plants (<300 kW) are available commercially, often combined with gas engines driving small generators, and demonstration plants in the range 10–30 MW have been in operation since the mid-1990s. The overall conversion efficiency from the energy of the solid fuel to that of the resulting gas varies widely, from as little as 40% or so in relatively simple systems, to 70% or more in the most sophisticated plants. The financial viability of biomass gasification on a large scale is not yet established; but the gas itself is not necessarily the desired end product. Much of its attraction stems from the future potential for three low-carbon biomass-based systems:

- electricity from integrated biomass-fuelled gas turbine plant
- liquid fuels as substitutes for petroleum products
- hydrogen or other fuel for fuel cells.

The first of these is briefly described in Box 4.8, the second is treated in Section 4.8 below; and fuels cells are discussed in Box 10.3 of Chapter 10.

BOX 4.8 **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 4.17(a)). 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 significant improvement is achieved in the **combined-cycle gas turbine** (**CCGT**) system. This makes use of the fact that the gases leaving the gas turbine are still hot enough to raise steam for a steam turbine. In order not to corrode or foul the turbine blades, the gases must be very clean – which is why nearly all present gas-turbine or CCGT plants burn natural gas.

However, if the output from a biomass gasifier can be cleaned and used to run the gas turbine, the possibility arises of a self-contained **biomass integrated gasification combined cycle** (**BIGCC**) system, for local power generation. Pilot demonstration plants using woody or bagasse fuel, with electrical outputs in the 5–10 MW range are being tested at the time of writing.

For more detailed accounts of steam and gas turbines and gasification processes in general, see the companion text. For descriptions of some biomass gasification plants, see Sims, 2002.

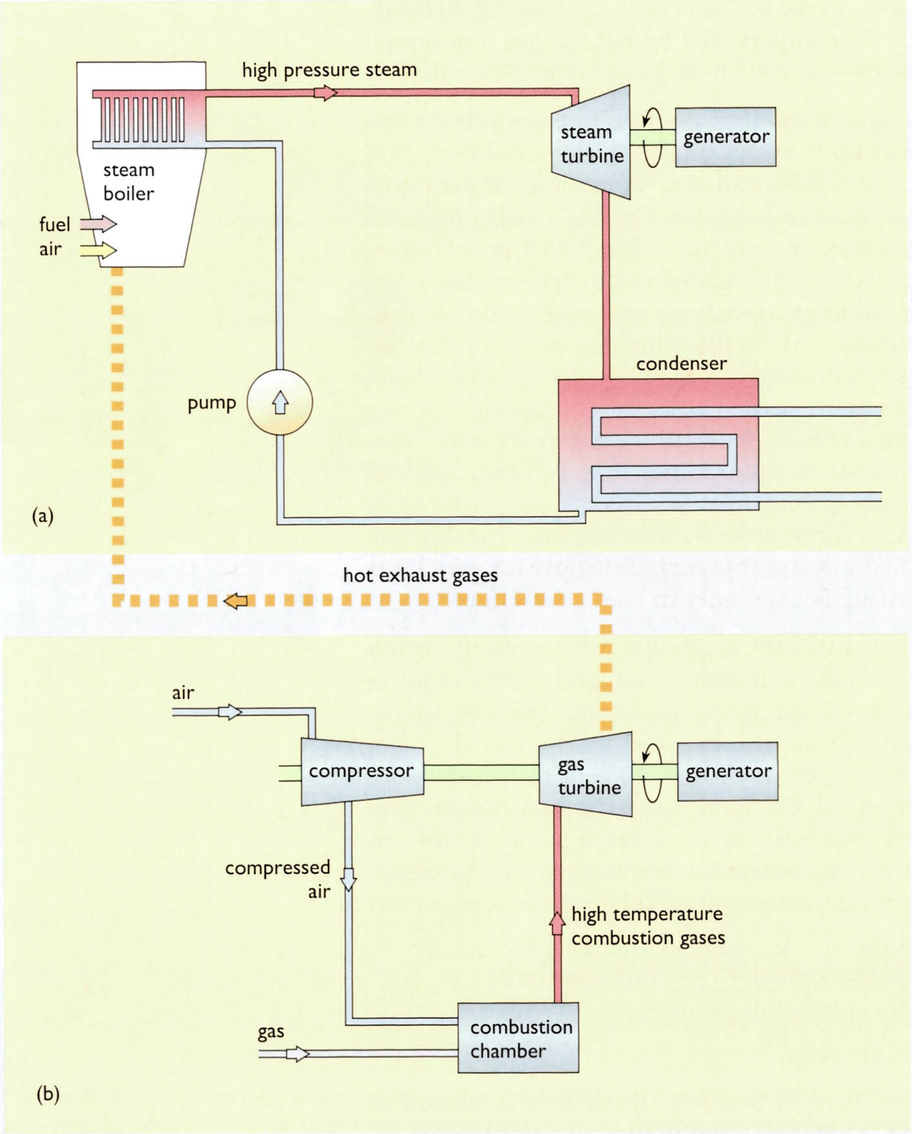

Figure 4.17 Types of generating system (a) conventional steam turbine: (b) simple gas turbine. In the CCGT plant, the gas turbine exhaust gases (dotted line) replace the fuel/air input as heat source for the boiler. For more details of turbines and gasification processes, see the companion text. For types of gasification plant, see Sims, 2002.

4.8 Production of liquid fuels from biomass

A major objective in bioenergy research is the production of liquid biofuels as substitutes for crude oil products. The three main approaches, treated in this section, could hardly be more different. The first is *thermochemistry*, which might be described as careful cookery. The second, *synthesis*, could be summarized as 'take it to pieces and start again'. The third method, *fermentation*, has of course been familiar to brewers and vintners for centuries.

Pyrolysis to produce bio-oil

Pyrolysis is the simplest and almost certainly the oldest method of processing one fuel in order to produce a better fuel. The traditional process that reduces wood to charcoal, today called **slow pyrolysis**, is very wasteful of energy, as we have seen. The term **pyrolysis** is now normally applied to processes where the aim is to collect the *volatile components* and condense them to produce a liquid fuel or **bio-oil**. As mentioned earlier, it is characteristic of biomass that the volatile matter carries more of the energy than the char, so this process should be more efficient.

The method involves heating the bio-material with a carefully controlled air supply. It must not burn, of course, and as the aim is a liquid product, gasification must be minimized. The resulting reactions are complex and hard to predict, giving a range of oils, acids, water, solid char and uncondensed gases, depending on the feedstock and operating conditions. The product, **bio-oil**, usually has about half the energy content of crude oil, and contains acid contaminants that must be removed. But it can be used as an oil substitute for heating or power generation, or could be refined to produce a range of chemicals and fuels.

Variations on the basic process include **solvolysis**, the use of organic solvents at 200–300 °C to dissolve the solids into an oil-like product, and **fast pyrolysis**, requiring temperatures of 500–1300 °C and high pressures (between 50 and 150 atmospheres). Fast pyrolysis, with capture of the volatiles, is used in the production of commercial charcoal, but at the time of writing, these methods for liquid fuels are at the pilot or demonstration stage (Sims, 2002).

Pyrolysis of wastes

Pyrolysis is an option for obtaining energy from waste materials, and pilot studies with MSW and plastics wastes have suggested relatively high energy efficiencies. But both pyrolysis and gasification (another option) seem likely to be considerably more expensive than incineration. Economies of scale, and perhaps greater acceptability than incineration, may mean better future prospects in more densely populated areas.

Synthesizing liquid fuels

One route from solid biomass to liquid biofuel starts with *gasification*. A gasifier using oxygen rather than air can produce a gas consisting mainly of H_2, CO and CO_2. Removal of the CO_2, and impurities such as tars, methane and traces of sulphur, leaves the highly active mixture of hydrogen and carbon monoxide called **synthesis gas**, or **syngas**, from which almost any hydrocarbon compound may be synthesized.

The first stage in the synthesis is a *shift reaction*, to adjust the proportions of H_2 and CO to the ratio required in the desired product. Methanol, for instance, is CH_3OH and therefore needs two H_2 molecules for each CO: a hydrogen-to-carbon monoxide ratio of 2:1. In the **Fischer-Tropsch** process, named for the chemists who developed it in the 1920s, the two components are passed over a suitable catalyst at high temperature and pressure, and the product, initially formed as a gas, is condensed. (A catalyst is a substance that influences a chemical reaction without itself being changed.)

The result, depending on the syngas composition and plant conditions, is a mixture of liquid and gaseous hydrocarbons. The gases can be recycled or used for heating, and the liquids can be up-graded and refined to produce vehicle fuels (Daey Ouwens and Küpers, 2003. For more on these processes, see also Chapter 7 of the companion text.)

Fermentation to produce ethanol

Fermentation is an **anaerobic biological** process in which sugars (e.g. $C_6H_{12}O_6$) are converted to alcohol by the action of micro-organisms, usually yeast. The required product, **ethanol** (C_2H_5OH), is separated from other components by distillation. Unlike methanol, ethanol cannot simply substitute for petrol, but it can be used as a gasoline extender in **gasohol**: petrol (gasoline) containing up to 26% ethanol – or possibly more in future. With suitable engine modifications (retuning, etc.) it can also be used directly.

Fermentation requires sugars, so the obvious source is sugar-cane, and this is the basis of Brazil's gasohol programme (see below). Plants whose main carbohydrate is starch (potatoes, maize, wheat) require initial processing to convert the starch to sugar, and this route is followed in the US, where the main source is maize. Even wood, with suitable pre-treatment, can be used as feedstock, but the processes are expensive, and the gasification/methanol route described above might be a better option.

The liquid resulting from fermentation contains about 10% ethanol, which is distilled off. The complete process requires a considerable heat input, usually supplied by crop residues. Table 4.4 shows the achievable yields of ethanol per tonne of biomass and per hectare of land for several crops. The energy content of ethanol is about 30 GJ t^{-1}, or 0.024 GJ per litre. Comparison of Tables 4.4 and 4.2 reveals that the conversion efficiency of fermentation is very poor indeed, but the technology is comparatively simple and plant costs low. And when the inputs are residues or surpluses and the output is a desirable product, low efficiency may be a price worth paying.

Table 4.4 Ethanol yields

Raw material	Litres per tonne[1]	Litres per hectare per year[2]
Sugar cane (harvested stalks)	70	400–12 000
Maize (grain)	360	250–2000
Cassava (roots)	180	500–4000
Sweet potatoes (roots)	120	1000–4500
Wood	160	160–4000[3]

[1] This depends mainly on the proportion of the raw material that can be fermented

[2] The ranges reflect world-wide differences in yield

[3] The upper figure is a theoretical maximum

Figure 4.18 Sugar cane

Brazil's PRO-ALCOOL programme, producing ethanol from sugar residues, is the world's largest commercial biomass system. It was established in 1975, when oil prices were high and sugar prices low, and during its first 25 years, the avoided fossil fuel imports saved $40 billion directly in hard currency, with further saving from reduced interest on foreign debt. Production has reached 15 billion litres per year at times. Most vehicles currently run on gasohol with 26% ethanol content, and 1999 estimates suggested that the programme was reducing annual greenhouse gas emissions by almost 13 Mt of carbon.

The economics of ethanol production are very uncertain. Its viability depends critically on world prices of sugar and crude oil, both of which have varied widely – and often rapidly – over the past 30 years. Within Brazil, disputes between the growers and distillers, the government and the national oil company have had their effect. Production rose and production costs fell during the 1990s, but at the time of writing, continuing depressed oil prices and the growth in Brazilian domestic crude oil production, coupled with the continued failure of growers, distillers and government to agree on a fair price, threaten the future expansion of large-scale liquid fuel production.

The USA has a long history of bio-ethanol production from **maize** (encouraged by Henry Ford, amongst others). But as with other biofuels enterprises, cheap petroleum destroyed the market. In the later twentieth century, the threat of oil shortages and the problem of surplus maize led to a minor revival, centred on the main grain-growing states of the Midwest. The US output of liquid biofuels has continued to rise at a few percent per year, reaching some 5 million tonnes in 2001 (IEA, 2003). As with sugar ethanol in Brazil, the economic viability of maize ethanol depends on two volatile factors, in this case the world prices of oil and grain. The possibility of grain price rises has encouraged the establishment of research projects investigating the potential use of alternative feedstocks such as agricultural residues, MSW and even woody energy crops.

Sweet-stemmed varieties of the grass-like grain crop, **sorghum**, are already used as feedstock for ethanol production in the USA and Brazil, using the same equipment as for sugar cane. Two crops per year are possible, and sorghum has a much lower water requirement than sugar cane. There is genetic potential for improved yields, and plant breeders are developing hybrids suitable for the European climate. An EU directive already allows up to 7% ethanol in gasoline throughout Europe, and there are tax incentives for other liquid biofuels (see below). Current US and European programmes are based on producing a useful product from surplus food, but if all costs are taken into account, the product is far from being competitive with conventional vehicle fuels. At a wheat price of £113 per tonne, the cost of producing bio-ethanol has been estimated to be about 36p per litre, considerably higher than the current *untaxed* petrol and diesel prices of under 20p. However, as discussed in the following sub-section, there is scope to encourage these biofuels by changing the tax regime.

Vegetable oils to biodiesel

In 1911 Dr Rudolf Diesel wrote, '*The diesel engine can be fed with vegetable oils and would help considerably in the development of the agriculture of the countries which will use it.*' He demonstrated the use of a variety of vegetable oils, and more have been tried since, but as we have seen in other cases, cheap crude oil came to dominate the market.

Vegetable oils are quite different from the liquid fuels discussed above. They occur naturally in the seeds of many plants, and are extracted by crushing. Their energy content of 37–39 GJ t^{-1} is only a little less than that of diesel (about 42 GJ t^{-1}). They can be burned directly in diesel engines, either pure or blended with diesel fuel, but incomplete combustion is a problem, leading to carbon build-up in the cylinders, and conversion of the vegetable oils to **biodiesel** is preferred.

The oils are compounds called triglycerides, whose large molecules are effectively various organic acids combined with glycerol (an alcohol). The main components of diesel oil, usually called esters, are organic acids combined with other, lighter alcohols. The conversion process, called *transesterification*, involves adding methanol or ethanol to the vegetable oil. This converts the triglycerides into esters of methanol or ethanol, together with free glycerol. The glycerol, a valuable by-product, is removed, and the excess alcohol extracted for recycling, leaving the biodiesel. No engine modification other than tuning is required to use it, although its lower energy content means that fuel consumption is about 10% higher.

Global production of biodiesel, from a variety of plants, is around 1.5 million tonnes per year and growing. In Europe, the potential of **rape methyl ester (RME)** from rape grown on set-aside land (Box 4.5) has generated interest. In France all diesel contains 5% RME, and oil from rape in the UK is exported to France. In the USA, production is based on oil from **soya** beans and **recycled cooking oil**. The UK government is also interested in this option for waste oils from chip shops, etc.

The estimated cost of producing biodiesel from rape seed at £110 per tonne is approximately 26p per litre, including credits for the glycerol and cattle-feed by-products. However, EU member states have been allowed since 1993 to adjust fuel tax levels to make biofuels more attractive. The UK tax was cut by 20p per litre in 2001, and biodiesel is now available from over 100 filling stations. Germany imposes no tax, and has more than 400 outlets selling biodiesel at a little under the normal (taxed) price for diesel.

A European Commission directive has proposed a target of 5.75% for the share of biofuels in the transport sector by 2010.

Using waste cooking oil could reduce costs, but collection logistics will probably restrict this to catering operations rather than domestic use. A British supermarket showed interest in converting oil from staff catering facilities to fuel for its vehicle fleet in 2002. (There were also reports in 2002 of UK drivers mixing vegetable oils from their local supermarkets with their diesel fuel. This is illegal – unless they take care to pay the tax – and may harm the engine.)

In countries with warmer climates, blends of up to 30% vegetable oil with diesel are used often without transesterification. Coconut oil is used in tractors and lorries in the Philippines, palm and castor oil in Brazil and sunflower oil in South Africa. However, the food and cosmetics markets can usually pay a better price, so these applications are limited to places where diesel fuel is expensive and in short supply.

4.9 Environmental benefits and impacts

An account of the methods used in assessing the environmental effects of energy systems appears in the companion text, Chapter 13, *Penalties*, which also presents the detailed results of a number of comparative studies. (See Boyle *et al*, 2003).

As we saw at the start of this chapter, the world's biomass plays a very basic role in maintaining the environment, so it is important to consider not only the *benefits* of bioenergy but the possible *deleterious* effects, global or local, of our interference with these natural processes. Space does not allow a detailed account of every effect of every form of bioenergy, so we'll concentrate in the following on the most significant benefits and impacts, considering first atmospheric emissions and then other aspects.

Atmospheric emissions

Carbon dioxide

The concept of 'fixing' atmospheric CO_2 by planting trees on a very large scale has attracted much attention. There is little doubt that the halting of deforestation and the replanting of large areas of trees would bring many environmental benefits, but absorption of carbon dioxide by a new forest plantation is a once-and-for-all measure, 'buying time' by fixing atmospheric CO_2 while the trees mature, say for 40–60 years. A wider bioenergy strategy, concentrating on the substitution of biofuels for fossil fuels may be a more effective lasting solution.

To analyse the benefits of substitution, it is essential to assess all the effects in a **life cycle analysis**. We'll start with just one form of energy in one context: electricity generating plants that are either current or near to commercial implementation in the UK. Table 4.5 shows the emissions of carbon dioxide and of the two main sources of acid rain, sulphur dioxide and oxides of nitrogen. The data are *life cycle emissions per unit of electrical output*, taking into account all the processes involved. For instance, the totals for energy crops include emissions associated with fertilizer production and the use of fossil fuel in processing or transporting the fuel. But there is also 'credit' for the CO_2 *removed* from the atmosphere by the growing crop.