# 27 Alternative Energy Sources

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## Contents

## 27.1 Introduction

The development of electricity generation from energy sources which are alternatives to hydrocarbons has become a major objective in Europe and elsewhere both for environmental reasons, principally the limitation of carbon dioxide emissions and, latterly, for the longer-term sustainability of energy supplies. The advent of major contributions from such sources is not without significant consequences, however, for the design and operation of electricity supply systems. Secure and low cost power supplies of high quality have been achieved based on historic energy supply patterns, network infrastructures, economies afforded by large-scale generating plant, system protection and control practices all of which would be affected by substantial levels of new distributed generation.

### 27.1.1 Embedded generation issues

At present virtually all small generating plants such as arising in most CHP and renewable power stations are connected to low voltage distribution networks not high voltage transmission grids. Individually most small embedded generating stations are not subject to central system control, partly because the high cost of conventional telemetry means that in the UK, for example, system control and data acquisition (SCADA) has only low penetration at voltages below 132 kV. At these levels, therefore, distribution networks operate largely with incomplete and uncertain information. In the main, any network problems caused by renewable generators arise either because of the intermittent nature of their output or their point of connection to the network, and not particularly because they are renewable energy sources. In fact some (e.g. biomass, landfill gas, etc.) are indistinguishable from conventional generators. Others (such as windfarms, tidal schemes, wave-power, etc.) can cause problems to the network operator, ranging from:

- System stability problems when a significant proportion of system demand is supplied by randomly intermittent generators, especially at light load. Small generators with low inertia do not provide the same buffering capacity as larger plant under the power swing conditions associated with system disturbances. If a generating plant fails, it is normally disconnected from the network to maintain system stability despite increased demand from the remaining generating sources. Only once the disconnected plant is running in a synchronised manner can it be reconnected to the grid.
- Voltage control and quality problems when generators embedded within the distribution network start/stop generating. This can cause other network users to suffer voltage fluctuation, dips and steps outside of the statutory limits and inject unwanted harmonics into the voltage waveform. The cure requires much more active operation of low-voltage tap-changers on transformers than these have been designed for leading to increased risk of failure, higher maintenance and replacement costs.
- Frequency control problems—many new forms of generation (CCGTs included) don't provide the expected response to low frequency, exposing users to more severe and more frequent excursions in system frequency.
- Large-scale renewable sources (tidal barrages, offshore wind and wave power, even new-generation nuclear) are likely to be situated remote from load centres. Exploitation of these sources requires major investment in reinforcing and expanding the transmission grid; however gaining rights of way to build new circuits can face determined and prolonged opposition from environmental lobbyists.
- The traditional network infrastructure causes additional difficulties in the siting of new generators. Distribution networks are generally designed and operated in radial configurations and are not designed to accommodate active sources of energy. This practice is based on the well established aim of minimising infrastructure costs associated with the number of conductors, protection equipment and switchgear size, apart from obviating the need for power flow control. Embedded generation adds to local fault levels and hence, sooner or later leads to the need for larger switchgear as well as the redesign of the protective systems. In addition and, as a consequence of this design practice, the distribution networks are often tapered in power flow capacity from the bulk supply point down to the customer in much the same way as a road or water network. Much renewable generation, e.g. wind, is sited away from the bulk supply points and nearer to the ends of the network, hence the difficulties in finding suitable connection points on the joint grounds of limited power flow and switchgear capacity.

With suitable engineering redesign and investment these problems can be overcome in time to a certain degree, but the costs of reinforcing the existing distribution network, upgrading control and protection systems, switchgear, transformers and reactive plant to cater for substantial embedded generation have to be considered. It is not clear how these costs will be apportioned in the privatised electricity supply industries now in existence. Furthermore it is not clear either how much randomly intermittent power from wind, wave or solar sources an electricity supply system can tolerate. According to the International Energy Agency as the contributions of these sources approaches 12% of power supplied and electricity not being capable of storage, policy makers need to start thinking about creating an energy buffer. At a 20% level it is contended that a buffer is absolutely necessary. There is, therefore, a technical limit to the development of renewable energy supplies if their output is geared solely to direct connection to the electricity supply system. Such a buffer can be supplied by pumped storage schemes in principle if enough storage capacity is installed, but the big development foreseen is the eventual move to a hydrogen economy with hydrogen from electrolysis providing the buffer and energy storage needed. In this context the development of fuel cells is a complementary activity to the development of renewable energy sources.

### 27.1.2 Energy costs

Two major methods for evaluating the unit costs of generation are:

- as annual costs per unit of kWh output relating to the costs appropriate to any particular year including a share of capital expenditure, and
- as a levelised cost per unit of kWh output which allocates lifetime production costs over the lifetime of the investment.

The latter method takes into account the time value of money and is the average present value cost in constant money terms per unit of energy produced at which the revenue from total lifetime output equals the total lifetime costs including capital, O and M and any other plant costs. This levelised cost method is recommended for use by the IEA[1] for comparison of generating plant costs under equivalent conditions because it covers the whole investment life of the system under consideration.

Ideally the costs should be evaluated at the user end point of consumption which would then include not only generation but transmission, distribution, system security, environmental, administration and other overhead costs; however beyond the generation plant boundaries the allocation of these extra costs is complex and maybe arbitrary. In electricity analysis, therefore, the bus-bar cost at the point of production is the only cost considered.

To relate capital cost to energy supplied the levelised cost per unit of kWh is found using a sinking fund method for uniform capital recovery whereby a constant capital charge rate ***A***, or annual payment, is made into the fund, which then accumulates interest and totals to the desired sum at the end of the period of, say, *N* years. Since no capital is redeemed interest is payable on the full capital amount ***P*** and the capital charge rate is

$$\boldsymbol{A} = \boldsymbol{P}\frac{i(1+i)^{\mathrm{N}}}{i(1+i)^{\mathrm{N}} - 1}$$

where *i* is the interest rate. Here the period N relates to the period for capital recovery rather than to the longer period of plant technical lifetime. The capital amount ***P*** is not usually the total capital cost of the project, because projects financed with private equity as well as loan, say in a 20%: 80% ratio, would be able to sustain lower energy production costs to cover the loan with returns to investors from whatever revenues from prices surplus to costs are possible.

Defining the factor ***R*** as $\boldsymbol{R} = i\,(1+i\,)^{\mathrm{N}}/i\,(1+i\,)^{\mathrm{N}} - 1$ then values of ***R*** are given in *Table 27.1* for periods of 3 to 25 years and for interest rates of 8 to 14%.

Given the rated plant full-load power generating capacity in kW, the load or capacity factor which is the equivalent proportion of the year that the plant would have to be generating at rated output to produce the actual energy output achieved and the total number of hours in a year (8760), then the energy ***E*** produced per annum in kWh is

$$\boldsymbol{E} = (\text{rated power full-load capacity}) \Leftarrow \\ \times (\text{capacity factor}) \times (8760) \Leftarrow$$

The cost of generation $\boldsymbol{C}_{\mathrm{cr}}$ attributable to capital recovery is then $\boldsymbol{C}_{\mathrm{cr}} = \boldsymbol{A}/\boldsymbol{E}$

To this cost must be added the annual operating costs including maintenance and, in the case of conventional plant, the annual fuel costs.

Comparisons of costs of energy produced from different renewable sources and from conventional generation plant involve a number of factors, which are inevitably site specific; therefore calculated costs should be considered only as indicative. The costs of any energy system could fall within a wide range depending on the specific conditions found at each site, the maturity of the technology, the economies of scale, the financing arrangements and the market conditions in which the electrical energy produced is traded.

**Table 27.1** Values of factor *R* for capital recovery

| *Periods* *N years* | *Interest rate* 8% | *Interest rate* 11% | *Interest rate* 14% |
|---|---|---|---|
| 3 | 0.388 | 0.409 | 0.431 |
| 5 | 0.251 | 0.271 | 0.291 |
| 10 | 0.149 | 0.170 | 0.192 |
| 15 | 0.117 | 0.139 | 0.163 |
| 20 | 0.102 | 0.126 | 0.151 |
| 25 | 0.094 | 0.119 | 0.146 |

## 27.2 Solar[2–9]

### 27.2.1 Photovoltaic systems

The present day market in the application of photovoltaic (PV) cells is defined by three sectors

- the *professional sector* which includes the powering of orbiting satellites or telecommunication repeaters in remote locations where the requirement for reliable, maintenance-free, independent power is essential,
- the *off-grid sector* which includes applications in developing countries, rural health, water pumping, irrigation and rural lighting and education, and
- the *grid-connected sector* where the PV electricity flows into a national grid. This sector is sub-divided again into two, that which forms part of centralised generation, e.g. for powering pumped storage schemes, and that which forms the larger sub-section of building integrated photovoltaic systems (BIPV).

#### *27.2.1.1 Principles*

When light strikes certain semiconducting materials such as silicon, gallium arsenide or cadmium sulphide, fabricated in the form of a p–n junction, an electric current can flow through an externally connected circuit. About 80% of PV cells manufactured are based on crystalline silicon. The silicon semiconductor band-gap energy of 1.1 eV, equivalent to a photon wavelength of 1100 nm, is the minimum threshold photon energy required to excite an electron-hole pair. Light of wavelength greater than 1100 nm, about one third of the spectral content of sunlight, does not have sufficient energy to create an electron-hole pair, whereas light of wavelength less than 1100 nm has sufficient energy to create an electron-hole pair, but only the band-gap energy can contribute to the cell voltage. The excess energy is lost in phonon transitions which heat up the cell. The theoretical efficiency of the silicon cell is thus around 30%. At present because of material imperfections the best laboratory cells are 24% efficient.

In bright sunlight, an irradiance of $1\,\mathrm{kW/m^2}$, a 10 cm square cell will give an output of about 0.5 V and 3 A, i.e. about 1.5 W of power, or $150\,\mathrm{W/m^2}$. Manufacturers quote the output of their cells for a sunlight intensity of $1.5\,\mathrm{kW/m^2}$ (similar to that of the Sahara Desert at noon). This standard output is labelled 'peak watts ' or '$\mathrm{W_p}$', and is measured at a standard temperature of 25°C. The power output of a solar cell varies with the intensity of light falling on it, which includes the angle of the sun to the plane of the module. The current output is halved if the light intensity is halved, but the voltage will drop by only a few per cent. The voltage output also depends on the temperature of the cell and decreases by about 0.5% for every degree Celsius rise in temperature above 25°C. Such cells need to be connected in series/parallel to provide a current-voltage relationship suitable for the load.

#### *27.2.1.2 Technology*

Three feasible broad groups of cell modules comprise crystalline flat plate, thin film flat plate and concentrator designs. Currently available commercial flat plate modules are based on either crystalline silicon or thin film amorphous silicon cells. There are also a number of concentrator installations in different countries based on single crystal silicon cells. Crystalline silicon flat plate modules dominate the power market, defined as arrays larger than $50\,\mathrm{W_p}$. Cells are made from single crystal or polycrystalline material with individual cells series-strung and then encapsulated behind low iron-content tempered glass. The best commercially available product at present is 16–17% efficient. Thin film cells based on materials having better photon absorption properties such as amorphous silicon, cadmium telluride and copper indium have had considerable development for the consumer market and also several large demonstration plants are in operation around the world. Low cost manufacturing of thin film solar cells has yet to be realised and, although having lower efficiencies than silicon cells, they hold the promise of being eventually cheaper to manufacture in high volume. The use of more expensive cells is possible by using optical concentration and high efficiency cells based both on gallium arsenide and silicon.

#### *27.2.1.3 Photovoltaic systems*

Typical modules produce about 14 V d.c. and about 3A under an irradiance of 1 kW/m$^2$. Higher power levels are obtained by series and/or parallel connections. Various module sizes rated from 30 W to 120 W are presently available. The module must also be mechanically supported to withstand wind loads and be correctly orientated to obtain maximum irradiance. The power output must be delivered in an acceptable form such as a constant d.c. voltage or 240 V, 50 Hz a.c. and this usually needs power-conditioning equipment. Presently available solar modules are manufactured to withstand extremes of climate and carry a twenty-year warranty to back up claims of trouble-free reliability.

The cost of a PV system comprises the manufacturing costs of silicon wafer production and assembly of modules plus the costs of installing the system. The silicon wafer cost is approximately 25% of the system cost at present of which 5% is the silicon feed-stock material cost, the wafer-to-module conversion cost represents a further 25% with the installation of the system comprising the mechanical support structure, cabling and inverters making up the remaining 50% of the total installed cost.

The PV industry is growing rapidly at about 30% per annum with significant urban markets developing in Germany, Holland, Japan and the USA stimulated by attractive subsidies. In the USA, for example, in 1998, there were 8500 solar buildings, up from only 2000 the previous year. The projected numbers of solar buildings for 2000, 2005, and 2010 are 51 000, 376 000 and 1 014 000 respectively. By way of illustration the Long Island Power Authority is providing a $4.5 million grant to help underwrite the capital cost of a photovoltaic system requiring 7 800 PV panels of varying sizes on the roofs of three buildings, having a capital cost of $9.3million (2001). The system will generate 1.5 MW of power during peak periods.

Guidelines and standards applicable to PV systems in various countries cover the requirements for safe installation of PV building-integrated systems applicable to PV modules and arrays, e.g. critical temperatures, voltage ratings, cable and insulation types, sizing for safe design, overcurrent protection, manual disconnects, grounding, anti-islanding protection, and in-surge and transient protection.

The major barriers to PV becoming a large-scale energy source are generated electricity costs and availability of raw materials. Today's PV systems sell for about \$6–\$10/$W_p$, with an implied electricity price of about \$0.4 to \$0.7/kWh in California and \$1.00/kWh in the UK. This compares with a domestic electricity price of around \$0.10/kWh in the UK and average generation costs of \$0.04 to \$0.05/kWh. Projections of future costs based on progress in PV technologies are consistent with module costs below \$0.5/$W_p$ (compared to \$3/$W_p$ today) with further reduction in installation costs. In the longer-term material availability may have to be addressed because several thin film PV technologies that are expected to have excellent cost potential use a rare raw material: germanium in amorphous silicon; tellurium in cadmium telluride; and indium and gallium in copper indium diselenide.

In the UK PV technology is likely to be grid-connected avoiding the cost of battery storage with integration into building facades or rooftops. Of all the renewable energy technologies contributing to the generation of electricity, photovoltaics is perhaps the one most easily integrated into the existing electricity supply structure, also with minimal environmental impact.

### 27.2.2 Solar thermal applications

Solar energy can be converted easily into useful heat and provide a significant proportion of space heating and hot water demand for low temperature-rise applications, e.g. domestic hot water.

#### *27.2.2.1 Active solar systems*

The most widely used active method for converting solar energy into heat is by the use of flat plate collectors comprising an absorber plate (transparent cover), tubes or channels integral with the collector absorber plate carrying water or other fluid, an absorber plate which is normally metal and with a black surface, insulation to minimise heat losses and a casing for protection against the weather, combined with pumps or fans for the circulation of the heat. Collectors come in a variety of forms, with combinations of flat, grooved and corrugated shapes for transferring the absorbed solar radiation from the surface. Solar ponds about 1 m deep with a blackened bottom can also be used as a collector offering the possibilities of achieving water temperatures up to 100°C with a collection efficiency of 15–20% using salt concentration to ensure that the density of water increases towards the bottom, thus preventing circulation by convection. Heat can be removed by circulating the lower levels of water through a heat exchanger without disturbing the upper layer. Advanced collectors are necessary for temperatures greater than 100°C because of the relatively large heat losses of simple flat plate collectors. Although there is a considerable technical potential market for active solar systems in North European countries such as the UK, for example, and, despite the publication of several Codes or Guides to good practice, the high costs of installations have reduced the development of the market in favour of alternative conventional sources of energy supply.

#### *27.2.2.2 Passive solar systems*

In passive systems use is made of the building materials and design for both space heating and cooling. By combining energy efficiency measures with passive solar design techniques for energy collection, storage and distribution energy costs in buildings can be greatly reduced from present day standards.[4,5] Several categories of passive systems exist including

- the 'direct gain' approach using windows as solar collectors,
- the Trombe or thermal storage wall in which the heat is stored in the wall which also absorbs the solar energy passing through the glazing,
- the solar greenhouse combining these two approaches whereby glazing, i.e. a greenhouse, is added to the outside

of a thermal storage wall facing south (in the northern hemisphere),

- the roof pond system in which a shallow pond or tank with moveable insulation is located on and covers the roof affording both heating and cooling options depending on the time of day covered and season and
- the natural convective loop using air.

Factors to be considered in passive solar design schemes include the influence of the local climate on the optimum design, the perceived merits or otherwise measured against energy use and cost, comfort and amenity value, public acceptance and the integration of energy use into the overall design process.

#### *27.2.2.3 Photochemical conversion*

In the photochemical conversion process, irradiation of an electrode/electrolyte system results in a current flow in an external circuit. The current may be generated by a photochemical reaction in the electrolyte, or by a photosensitive electrode. Devices based on this effect, the absorption of solar photons in a molecule producing an excited state or alternatively in a semiconductor raising electrons from the valence band to the conduction band, may be used either to produce electric power directly or to produce a chemical product (photo electrolysis). The latter process stores the energy and regenerates the reactants on subsequent conversion to electricity. It is this capacity for energy storage that makes the devices based on the electrochemical effect particularly attractive for solar energy conversion. So far, however, only low efficiencies have been obtained and the process is at present almost entirely experimental. The majority of photochemical reactions are exothermic and not suitable for converting solar radiation into stored chemical energy. The known endothermic (energy storing) reactions that occur with visible light are, in theory, capable of producing valuable chemical fuels. A major problem, however, has been that most of these endothermic reactions reverse too quickly to store the energy of absorbed light.

#### *27.2.2.4 Chromogenic materials*

Most of the literature on this subject concerns small-scale electronic information display, but chromogenic materials offer also the possibility of developing advanced glazing which combines variable control of solar gain with efficient thermal insulation. Electrochromic windows are essentially electric cells comprising an electrochromic layer and a counter-electrode, or ion storage layer separated by an ion conductor and sandwiched between two transparent electronic conductors that are deposited onto transparent substrates, e.g. glass or polymeric materials. In operation a d.c. electric field is applied across the transparent conductors and ions are driven either into or out of the electrochromic layer. In addition the electrochromic layer may be caused to bleach or to colour in a reversible way under the influence of the field causing reflectance or absorptance modulation of visible and near infrared electromagnetic radiation and hence changes in the optical properties of the window.

#### *27.2.2.5 Transparent insulation materials*

Transparent (or translucent) insulation materials (TIMs) are a relatively new class of materials that combine the uses of glazing and insulation. With these materials high transmission of light and heat from the sun (solar gain), good insulation (U-value), i.e. low conduction of thermal wavelengths, and strong convection suppressant characteristics are possible.

## 27.3 Marine energy[10–16]

The main potential sources of marine energy are tides, marine currents caused by tidal movement but including other effects as well, waves and ocean thermal energy.

### 27.3.1 Tidal energy

There are two types of technology involved in extracting energy from the tides, the first capturing and subsequently using the potential energy within a storage basin, the second converting the kinetic energy of tidal streams. The concept of installing turbines in a barrage that encloses inlets or estuaries is well established, whereas the use of tidal streams, although considered for some time, has recently seen a marked increase in interest through comprehensive studies and progress towards demonstration projects.[10]

The sea level varies approximately sinusoidally with a 12.4-hour period, the diurnal ebb and flow cycle, superimposed on a longer sinusoid with a period of 353 h, the spring-neap cycle. When the sun and the moon are almost in line with the earth the tides have their maximum amplitude and are known as the spring tides; when the moon–earth–sun angle is a right angle the tides are at minimum amplitude and are known as the neap tides. The ratio between the amplitudes of the maximum spring tide and the minimum neap tide can be up to as much as 3 to 1. Smaller seasonal variations also occur. The peak-to-peak amplitude of the tidal variation is known as the tidal range. In mid-ocean this range is about 1 m, but it is often amplified in coastal areas by a complex interaction with coastal features. The greatest amplitude occurs in estuaries where the tide is in resonance condition with the advancing tidal wave interacting with the reflected waves from the side of the estuary.

#### *27.3.1.1 Tidal barrages*

The simplest method of extracting energy from the tide is to build a dam (barrage) across an estuary or inlet, the dam containing turbines to generate electricity. In its most basic form the rising 'flood' tide enters the basin through gated openings or sluices and through the turbines idling in reverse. At high tide all openings are closed until the tide has ebbed sufficiently to develop a useful head across the barrage. The turbines are then opened and generate electricity for several hours until the difference in water level between the emptying basin and the next flood tide has dropped to the minimum at which the turbines can operate. Shortly afterwards the levels will be equal, the sluices are opened and the cycle repeats. There are alternative methods of operation, the main options being generating at ebb tide only with or without using the turbines also as pumps at high tide to raise the level of water in the basin and generating during both flood and ebb tides. Studies have shown that the method of operation that results in the lowest unit cost of energy is either simple ebb generation or ebb generation with pumping at high tide. With ebb generation electricity is produced for 5–6 h during spring tides and about 3 h during neap tides out of a tidal cycle lasting approximately 12.4 h; thus a tidal barrage produces two blocks of energy each day, the size and timing of which follows the lunar cycle. As the generation period is about 1 h later each day, the generation (and pumping if used) needs

**Table 27.2** Mean tidal range in selected locations[11]

| *Location* | *Range* (m) |
|---|---|
| Bay of Fundy Canada | 10.8 |
| Severn Estuary, UK | 8.8 |
| Rance Estuary, France | 8.45 |
| Passamaquoddy bay, USA | 5.46 |
| Solway Firth, UK | 5.1 |

to be planned in advance to integrate with the demand and supply of the grid.

Assessments of technical and economic feasibility of tidal barrages are site specific. Some locations are particularly favourable for large tidal schemes because of the focusing and concentrating effect obtained by the bays or estuaries. Typical ranges are shown in *Table 27.2* which includes the world's largest tidal range in the Bay of Fundy and Europe's largest, the Severn Estuary.

Other sites representing important energy resources include Alaska (Cook Inlet), Argentine (San Jose), Australia (north west coast), Brazil (north coast), China (Yellow Sea), France (Iles de Chausee), India (Gulf of Cambay, Gulf of Katchch), South Korea (west coast), Russia (Okhotsk Sea, Jugursk Bay).[12]

The largest scheme in operation is the 240 MW barrage at St Malo in the Rance Estuary France. Work on the Rance site commenced in June 1960, the final closure against the sea in July 1963 and the last of the 24 × 10 MW turbines being commissioned in November 1967. The overall length of the barrage is 700 m. Tides follow a two-week cycle throughout the year. During the first week the tidal range is between 9 m and 12 m and in the second week between 5 m and 9 m. For the lower ranges electricity is generated on the ebb tide with the basin level increased by pumping while for the higher ranges the electricity is generated during both ebb and flood tides, sometimes augmented by pumping. The output is computer controlled and optimised to match the needs of the French national grid. The nominal average output of between 50 and 65 MW is thus not the maximum that could be obtained, but contributes maximum savings to the grid.

While La Rance electricity is the cheapest electricity on the French national grid Electricité de France say that it would be too expensive to build any further power stations. The same conclusion applies to the proposed Severn Barrage scheme in the UK. This larger project would involve a single basin ebb generation scheme with a 13 km barrage. The estimated total installed capacity would be 8640 MW obtained from 216 turbine generators, each 9 m in diameter and rated at 40 MW with an annual output of about 17 TWh. The nominal lifetime is taken to be 120 years, but in practice with maintenance and turbine replacement as necessary is indefinite. Elsewhere in the UK the second largest project would be the Mersey Barrage. Here the installed capacity would be only 600 MW, but there would be substantial benefits to the local economy. Overall in the UK the theoretical tidal barrage capacity is considered to be approximately 25 GW.

Tidal barrage schemes have a large impact on an estuary. With a reduced tidal range above the barrage there are potential changes to land drainage, fish migration, navigation of ships, wading bird activities plus the possible increased sedimentation due to altered channel turbulence and flow in the estuary. Several advantages follow from building a barrage, however, through the provision of a route for road traffic across an estuary and with the reduced tidal range come increased opportunities for recreational sailing and water sports.

### *27.3.1.2 Marine currents*[10]

Relatively rapid marine currents exist at locations where natural marine flows occur through constraining channels such as straits between islands, shallows between open seas and around the ends of headlands. Marine currents are driven primarily by the tides, but also to a lesser extent by coriolis forces due to the earth's rotation, salinity and temperature differences between sea areas.

Studies of the European resources showed 106 locations suitable for exploitation with a total capacity of some 12 GW yielding about 48 TWh per annum. Other large resources exist in SE Asia, Canada, the SE coast of South Africa and elsewhere. Typical velocities at peak spring tides are in the region of 2 to 3 m/s or more. The main requirements are fast flowing water, a relatively uniform seabed to minimise turbulence, sufficient depth of water to allow large enough turbines to be installed, such conditions to extend over as wide an area as possible to allow the installation of enough turbines to make the project cost effective, free from shipping constraints and near enough to a shore-based electricity supply network capable of taking the power delivered.

The extraction of energy from marine currents by means of propeller turbine rotors is governed by the same equations as for wind turbines, thus the power theoretically available from a stream of water through a turbine is

$$P = 0.5 d_w A V^3$$

where $P$ is the power, $d_w$ the density of water, $A$ the area swept by the rotor blades and $V$ the stream velocity. The power density of water compared to that of wind may be seen from the *Table 27.3* for different velocities assuming a density for salt water of 1030 kg/m$^3$ and an air density of 1.2473 kg/m$^3$ corresponding to air at 10°C.

The maximum amount of energy that can be extracted is 16/27 or 0.59259 of the theoretically available energy (the Betz limit) and, as for wind turbines, this efficiency can only be approached by careful blade design.

In contrast to wind turbines of similar output the high power densities achieved with streams of flowing water at the velocities encountered mean that large thrust forces are applied to marine turbines. *Figure 27.1* illustrates the power output and speed of a marine turbine for different rotor sizes assuming a stream velocity of 2 m/s and a conversion efficiency of 30%[10] with the possible overload torque and thrust loads encountered at the higher velocity of 4 m/s.

**Table 27.3** Relative power densities of marine currents and air at different velocities

| *Velocity* m/s | *Power density marine* kW/m$^2$ | *Power density wind* kW/m$^2$ |
|---|---|---|
| 1 | 0.52 | — |
| 2 | 4.12 | — |
| 3 | 13.91 | 0.2 |
| 10 | — | 0.62 |
| 15 | — | 2.10 |
| 20 | — | 4.99 |

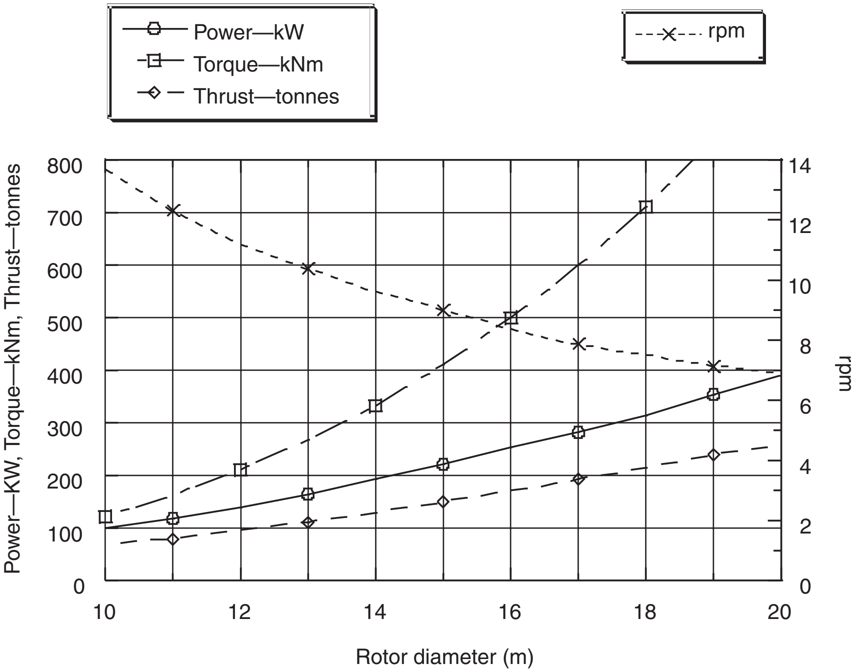


**Figure 27.1** Typical performance characteristics of marine turbines in 2 m/s tidal stream and 30% efficiency

The high axial thrust requires the turbine to be attached to a structure which is either anchored firmly to the seabed via gravity based or piled platform structures or floated beneath a vessel held by high tension moorings. Various designs are possible for the power train linking the horizontally mounted turbine to the generator from which output is delivered via a marine cable laid across the seabed to the shore at voltages of 11 or 33 kV.

## 27.3.2 Wave energy

### *27.3.2.1 Resources*

The oceans act as an integrator of wind energy. Waves arriving at any point can have originated from storms many hundreds of kilometres distant, the 'swell' sea, or from local wind conditions, the 'wind' sea. The distance from the origin of the swell waves is known as the fetch. As a general rule coastlines with an ocean fetch of greater than 400 km are suitable sites for recovering wave energy with the greatest resources being available between latitudes 30° and 60° in the Northern and Southern hemispheres.

In the UK alone it has been estimated that the recoverable wave energy resource exceeds total UK electricity demand. Estimates of the total power available for wave energy systems in the UK in the mid-1970s were based on data gathered from the weathership *India* (50°N, 19°W). Translating this data into wave power likely to be obtained from shoreline devices gave the analysis summarised in *Table 27.4*.

Measurements reported by the then CEGB in 1983 at inshore sites in the UK showed power levels between 40 and 50 kW m$^{-1}$ of wave front in water about 50 m deep

**Table 27.4** Achievable wave power resource in the UK[13]

| | |
|---|---|
| TOTAL RESOURCE Estimated in 1974 by assuming weathership data of 80 kW/m mean annual output applied to 1500 km of UK coastline | 120 GW |
| GEOGRAPHICAL LIMITATIONS Land masses prevent formation of energetic waves from easterly direction and Eire screening part of UK coastline | −72 GW |
| DEVICE CONFIGURATION LIMITATIONS Waves from different directions are not absorbed with equal efficiency by a line of devices. Directionality factor = 0.76 | −12 GW |
| STATION DESIGN LIMITATIONS Some sites are not suitable: devices must be spaced apart and permit navigation. Device/space ration = 0.75 | −9 GW |
| DEVICE CAPTURE LIMITATIONS Efficiency of power absorption varies with wavelength. Some power is rejected. Overall efficiency = 40% | −16 GW |
| POWER TRAIN LIMITATIONS Losses due to efficiencies of turbine, generator, transmission system. Overall efficiency = 50% | −5 GW |
| AVAILABLE RESOURCE May be subject to further limitations both environmental and economic | 6 GW |

near South Uist and 25 kW $m^{-1}$ off the north-east coasts of England or south-west Wales.

Further assessments made in 1988[14] gave a larger technical potential of 30 GW capable of providing some 50 TWh $yr^{-1}$, mainly off the Western Isles of Scotland and the coast of Cornwall. Such estimates have to be moderated by the lack of electrical transmission network infrastructure in NW Scotland and between Scotland and England that need to be installed if wave power is to contribute significantly to the UK demand for electrical energy.

#### *27.3.2.2 Device design*

Over three hundred ideas have been considered in the UK Department of Energy programme.[13] In general three main approaches to capturing wave energy are as follows:

(i) *Floating or pitching devices* These devices generate electricity from the bobbing or pitching action of a floating object. Examples include tethered buoy structures where the rise and fall is restrained by the mooring with energy extracted from a pump in the mooring. Alternatively the device can be mounted to a floating raft or fixed to the sea floor where energy is extracted from the relative motion between inner and outer parts of converters mounted on a common frame or spine across the wave front or to hinged wave-contour structures perpendicular to the wave front where the energy is extracted from the relative motion of adjacent sections.

(ii) *Oscillating water columns (OWC)* These devices generate electricity from airflow caused by the wave-driven rise and fall of water in wave energy collectors which are in the form of a partially submerged shell into which seawater is free to enter and leave. As the water enters or leaves a column of air, contained above the water level, is alternately compressed and decompressed to generate an alternating stream of high velocity air in an exit blowhole. If this air stream is allowed to flow to and from the atmosphere via a pneumatic turbine, energy can be extracted from the system and used to generate electricity. Designs exist for 2 MW near shore gravity anchored wave stations designed for regional power generation and coastal protection and for larger 3.5 MW near shore combined wave and wind stations which can be constructed also in multiple units when larger quantities of electricity are required.[16]

(iii) *Wave surge or focusing devices* These devices rely either on naturally occurring 'tapered channel' gullies in shorelines or on a shore-mounted structure to channel and concentrate the waves. 'Overtopping' schemes as in the 'Tapchan' system in Norway, use the enhanced height of the wave action to cause water to flow over a dam where it is stored and allowed to run out through a turbine when needed. An alternative approach is to combine the tapered channel approach with the oscillating water column. Such a scheme is the first commercial wave power station on the Scottish island of Islay based on the LIMPET 500, a 0.5 MW shoreline wave power station.

#### *27.3.2.3 Mooring and anchoring*

The provision of storm resistant mooring and anchoring for floating wave energy devices especially in deep water presents difficult technical problems which have not been readily solved. In general the cost of mooring and anchoring, or the provision of seabed attachment, together with the cost of the initial device installation would be a significant proportion of the overall capital costs. It could range from 10 to 15% for floating devices and possibly up to 30% for devices fixed to the seabed. The latter systems would be virtually maintenance free whereas moorings require periodic inspection and replacement, thereby incurring an extra operational cost.

#### *27.3.2.4 Power conversion and transmission*

Various hydraulic and mechanical systems have been proposed, but the largest numbers of designs use air as a working fluid. Either the flow of air is rectified by valves, or it flows backwards and forwards through a turbine such as the Wells turbine. Wells turbines have the property of turning in the same direction regardless of which way the air is flowing across the turbine blades. No large wave power scheme comprising many devices exists at present, but in principle the generation of electricity by means of a number of small alternators can be aggregated by a d.c. system for transmission to shore and thence inverted by power electronics to the electricity supply network requirements.[12,13]

#### *27.3.2.5 Environmental acceptability*

Wave power development has not yet progressed sufficiently to encounter institutionalised environmental opposition. The establishment of large schemes offshore, however, would raise questions for the shipping and fishing industries. In addition changes to shoreline wave environments and noise, particularly from the oscillating water column devices, would have to be considered unless the installations were suitable distances from habitation.

#### *27.3.2.6 Economics*

To date the costs of prospective wave power schemes has led to unfavourable comparisons with alternative ways of harnessing renewable energy such as wind. Wave power generators are as yet only likely to be useful at suitable coastal sites, especially on remote islands where the costs of conventional diesel generated power is high. In addition for coastal sites in areas of outstanding natural beauty they will have less environmental impact than large wind turbines and thus may be more readily acceptable.

## 27.4 Hydro

The technology for the use of hydropower for the direct generation of electricity has developed from wooden water wheels (overshot, undershot and crossflow) through to the Francis, Kaplan, Pelton, Crossflow and Turgo turbines of the 20th century. In developed countries the larger hydro resources were among the first to be exploited. Attention has focused more recently on smaller resources which are generally classified as shown in *Table 27.5*[3] (other size classifications are also found in the literature).

**Table 27.5** Definition of hydro scheme size

| | |
|---|---|
| Large | 50 MW and above |
| Small | 5 MW to 50 MW |
| Mini | 500 kW to 5 MW |
| Micro | 500 kW and below |

By the 1980s the country with the greatest experience in small-scale hydropower development was the People's Republic of China where nearly 100 000 plants had been constructed in the previous twenty years.

With a mature technology the investigation, design and construction of conventional large-scale hydroelectric schemes is well defined and understood and can be costed with reasonable certainty. For small schemes at the mini and micro scale, however, economic constraints demand an innovative approach. Novel low head designs for prime-movers together with a trend towards the use of off-the shelf components and plastics for small impeller-type turbines, the use of micro and power electronics in generation and again the use of plastics for pipelines in the civil engineering works all contribute to extending the boundaries of economic viability.

The distinctive features of small hydropower plants include being usually run-of-river type, construction in a relatively short period of time, using well developed technology with an overall efficiency of over 80% and having automatic operating systems with low operation and maintenance costs.

As for all renewable resources the size of an exploitable resource depends on both technical and economic factors. For hydro the broad categories are

- the gross river potential which is approximately the summation of (annual run-off $\times$ potential head),
- the exploitable technical potential which is the gross river potential less the potential which is technically impossible to develop,
- the economic potential which is the technical potential less the potential which is uneconomic to develop, and more recently in the history of this technology,
- the environmentally acceptable potential which is the economic potential less the potential which is considered environmentally unacceptable to develop.

Without significant storage capacity large variations in available water flow may be experienced. In the UK the capacity factor for hydro, i.e. the ratio of actual annual energy generated to energy produced at rated output over twelve months, is approximately 30% which is nearly the same as for wind energy. Small-scale hydro-schemes with turbines having sufficient rotational velocity can employ either induction or synchronous generators. Low-head run-of-river turbines run more slowly and so need either a gearbox or a large multiple pole generator for energy conversion.

A more detailed discussion of hydroelectric plant is given in Section 26.4.

## 27.5 Wind[17–25]

### 27.5.1 Wind energy

The annual energy available from a wind turbine in any particular location depends on the wind speed at hub height, which in turn depends on the shape of the local landscape, the height of the turbine above the ground and the annual climatic cycle. An empirical relationship between mean wind velocity $V$ and turbine height $H$ is $V = H^a$ where $a$ has a value of 0.13 in the UK for open, level ground, rising to 0.25 for an urban site and to 0.33 for a city site.[8] An ideal site is a long, gently sloping hill.

Offshore wind speeds are generally higher than on land, e.g. ten kilometres from the shore speeds are typically 1 m/s higher than on land. Although wind/wave interactions exist, turbulence is lower which reduces the fatigue loading on the turbine blades. It is offshore where the very large wind-farms of several tens or even hundreds of MW in size are anticipated in the future.

### 27.5.2 Wind turbines

The theoretical power in an air stream is 0.5 $d_a AV^3$ where $d_a$ is the density of air, A the cross-sectional area and $V$ the velocity. The actual power $P$ extracted by a wind turbine, however, is of the same form as for water turbines

$$P = C(0.5 d_a A V^3)$$

where $C$ is a coefficient of performance or power coefficient. The German Engineer Betz showed in 1927 that the maximum power extracted from a moving air stream to be 16/27 or 0.59259 of the theoretically available power. This efficiency can only be approached by careful blade design with blade tip speeds a factor of six times wind velocity and is known as the Betz limit. Modern designs of wind turbines for electricity generation operate with a power coefficient ($C$) of about 0.4, with the major losses caused by drag on the blades and the swirl imparted to the air flow by the preceding rotating blades. Any wind turbine will operate only between a minimum starting wind velocity value, $V_S$, and its rated value $V_R$. Typically the ratio $V_R/V_S$ is between 2 and 3, although if the pitch of the blades can be altered at velocities greater than $V_R$ then the turbine should continue to operate at its rated output, the upper limit being set by design limitations. Depending on the location the wind speed may be less than $V_S$ for 25% of the year when the turbine is shut down and the annual load factor, the ratio of energy produced to the energy that would be produced if run at maximum rated output over the whole year, is typically between 25% and 35%. A typical operating power characteristic is shown in *Figure 27.2*.

In general machines are designed to operate with a peak output in the range 250–500 W/m$^2$; thus 20 m machines have ratings of around 200 kW, 30 m machines around 300 kW and 50 m machines around 1 MW. Power limitation is accomplished either by using feathered blades in larger machines, with feathering along the whole blade length, or in smaller machines by taking advantage of the natural tendency of blades to stall as the angle of attack increases in high winds. Current commercial wind turbines tend to operate at a fixed speed with tip speeds of around 50–80 m/s for power generation and slower speeds for high torque applications such as pumping.

The technical options available to designers of wind turbines and the interaction of option choices in the determination of machine weight and cost are discussed.[17] This work examines the extensive debate surrounding the optimal size of machines and the engineering implications of a move from heavy, stiff designs to more lightweight, compliant designs. Typical turbine characteristics are summarised in *Table 27.6*.[21]

### 27.5.3 Wind generators

With wind speed fluctuations being inevitable it is important to damp out the consequent driving torque oscillations in the generator. For network-connected fixed speed turbines synchronous generators do not provide adequate damping which must be supplied elsewhere in the transmission otherwise power fluctuations and blade loads may be unacceptable; hence most use 4- or 6-pole induction generators. Induction generators provide inherent damping where

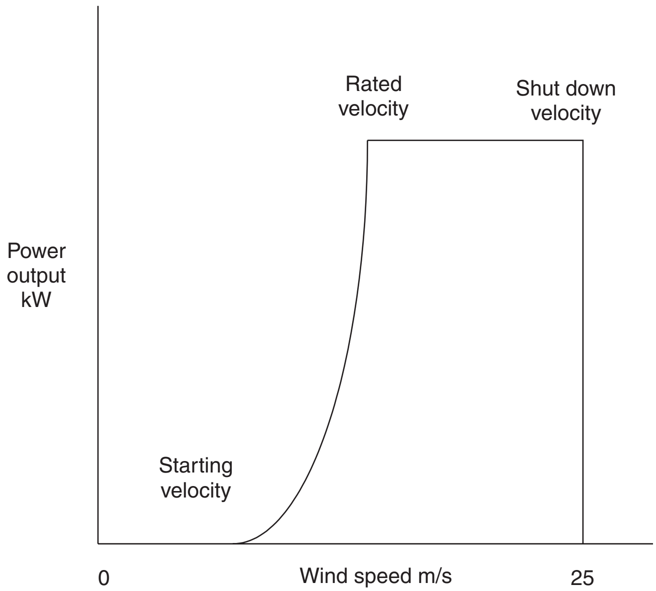


**Figure 27.2** Typical wind turbine power/wind-speed operating characteristic

**Table 27.6** Typical wind turbine characteristics

| | |
|---|---|
| Ratings | 1 to 2 MW now available and increasing |
| Availability | 98–99%, a mature reliable technology |
| Rotor diameter | Up to 80 m, larger diameters to follow |
| Number of blades | Majority now three, reducing percentage of two or even one |
| Blade material | Glass-reinforced plastic or wood-epoxy |
| Rotor orientation | Mostly upwind of tower, some downwind |
| Rotational speed | Usually constant, c. 25 rpm at 52 m diameter, some two speed and variable speed |
| Power control | Stall control in high winds with fixed blades, pitch control where all or part of blades rotate to limit power |
| Power train | Step-up gear boxes most common, direct drive without gearbox now also used |
| Yaw control | Wind direction sensors linked to powered rotor alignment, some passive yaw control |
| Towers | Cylindrical steel construction, concrete towers used for some large machines |

the damping is provided by the slip speed difference between the rotor and stator rotating mmf, but suffer from the disadvantage of drawing reactive power from the system and also from drawing high starting currents which may cause local flicker. Typically the induction generator is wound for 690 V, 1500 or 1000 rpm operation and generally of squirrel-cage construction. Connection to the network is via power-factor correction capacitors and power electronic converters to accommodate starting conditions or, in the case of variable speed operation, to decouple the speed of the rotor from the frequency of the network.

### 27.5.4 Economics

Onshore wind farms are relatively competitive. Costs have fallen from 8.6 pence per kWh in 1992 to an average of 2.88 pence per kWh for the new farms coming on line now. They are among the most competitive renewable energy plants and are less expensive than some new coal plants. Electricity from offshore wind farms remains uncompetitive, however, at present in comparison with electrical energy provided by conventional power sources.

The estimate of capital costs of wind farms in the USA is $983/kW (1999 prices).[22] The same source gives a typical capacity factor at 32% although the average for UK wind farms is approximately 24%[23] as shown in *Figure 27.3* which illustrates typical monthly variation in capacity.

European installed costs are quoted at

- Euros 875/kW[24] onshore and Euros 1600/kW offshore,[25]
- 15 year depreciation, 7% discount rate
- O and M costs: Euros 20/kW/yr + Euros 0.004/kWh.

Using these figures *Table 27.7* illustrates the calculation of the generation costs for a 50 MW wind farm assuming a capacity factor of 28% giving a total cost of Euros 0.051/kWh or 3.07 p/kWh.

*Figure 27.4* shows the effect of different capital recovery periods where for short pay-back times the costs are prohibitive and the value of longer term guaranteed support over fifteen years can be seen. With significant differences in generation costs being measured in tenths of p/kWh the importance of capacity factors, i.e. choice of site, turbine hub height, etc., can also be appreciated.

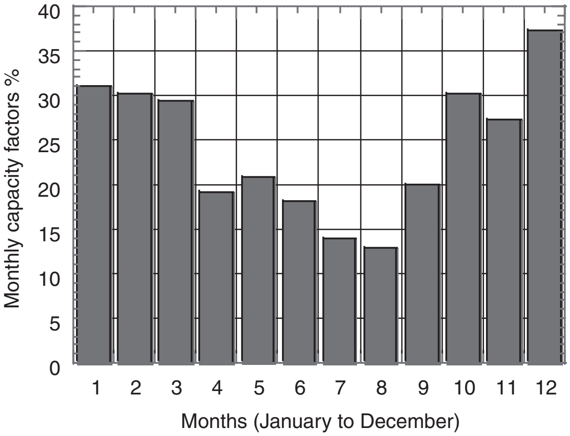


**Figure 27.3** Wind farm typical monthly capacity factors (Annual average 24%)

**Table 27.7** Generation cost estimates

| | | |
|---|---|---|
| Capital cost | Euros/kW | 875 |
| Total capital cost, ***P*** | Euros | 875 × 50 000 |
| Annual energy generated, ***E*** | | |
| at 28% capacity factor | kWh/yr | 122 640 000 |
| Discount rate | % | 7 |
| Capital recovery period | years | 15 |
| ***R*** (see section 27.3) | | 0.110 |
| Capital cost ***A/E = P × R/E*** | | |
| for 24% capacity factor | Euros/kWh | 0.039 |
| O & M costs | | |
| maintenance | Euros/kWh | 0.008 |
| operation | Euros/kWh | 0.004 |
| TOTAL generating cost | Euros/kWh | 0.051 |

### 27.5.5 Environmental issues

Wind energy is a non-polluting form of energy fulfilling the aims of present governments to replace polluting and non-renewable hydrocarbon-generated electrical power with power generated from cleaner forms of energy. In the course of the development of the industry, however, other forms of pollution have been noted and been the object of much debate and hostility. The principle environmental issues to be considered in deploying wind farms are:

- Visual and landscape impact;
- Noise;
- Electromagnetic interference;
- Effect on birds and wildlife; and
- Land use.

The same considerations apply, however, to all other forms of renewable energy exploitation. Wind energy has been in the forefront of development, deployment and commercialisation so has been the first renewable industry to meet the environmental objections and constraints.

Chief among these effects are visual pollution and noise. Visual pollution, although subjective, is easy to comprehend arising simply from the juxtaposition of industrial plant in areas of outstanding natural beauty, i.e. unspoiled countryside. Other wind-turbine sites in 'brown field' sites in or near urban areas where industry has been before have not created the same opposition and indeed have been taken as symbols of regeneration.

Noise is more of a problem inasmuch as there appears to be some evidence of low frequency (infrasound) noise effects near some sites, but the data is sparse. Early problems of noisy gears have largely abated with better design and manufacture. The level of noise of the aerodynamically generated swishing noise of the turbine blades, however, varies from site to site and can be negligible. Particularly strange effects have been reported from Montgomeryshire in Wales where the existence of steep nearby valleys seems to act in some cases as a means of focusing noise at different places away from the wind farm sites.[18,19]

Offshore wind farms will have less of these problems, but for on-shore sites local objections have meant that the majority of planning applications in the UK have been refused so it is vitally important that projects are properly and sensitively integrated into the landscape and developed in consultation with local communities.[20]

## 27.6 Geothermal energy

The Earth is an almost infinite source of heat with a continuous heat flow of some $10^{13}$ J/s. Unlike the other renewable

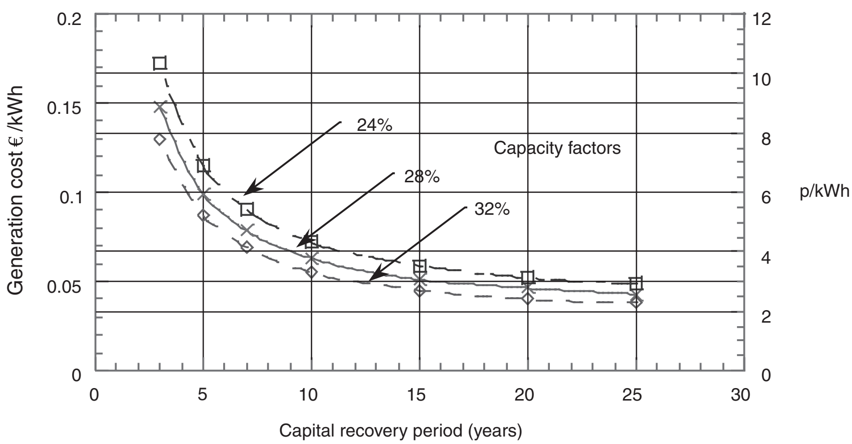


**Figure 27.4** The influence of capital recovery periods and capacity factors on wind generation costs

resources, which are intermittent, geothermal energy can deliver a constant source of power until the reservoir is exhausted. There are two possible techniques for exploiting geothermal energy:

(1) use of existing hydrothermal sources;
(2) to attempt to extract heat from hot dry impermeable rocks deep below the surface.

The first technique is now commercially established, whilst the second is still at the research and development stage.

### 27.6.1 Hydrothermal sources

Although steam and hot water come naturally to the surface of the earth in some locations, for large-scale use boreholes are normally sunk with depths of up to 3 km, releasing steam and water at temperatures of 200–300°C and pressures of up to 3000 kN/$m^2$.

Flowing well-head steam pressures vary between 200 and 1500 kN/$m^2$. From the well heads the steam is often transmitted by pipelines of up to 1 m diameter over distances up to about 3 km to the central power station. Water separators are usually required, as superheating the steam to minimise wetness requires fossil fuel, the use of which is usually uneconomical. Care must be taken in the choice of materials for the plant, as the steam may contain solid and gaseous impurities. Steam may come from several bore holes at different pressures, so that the steam layout of the generating station may involve two or three different pressures in cascade. If water quality is satisfactory, direct use of the steam in turbines is possible. In most cases jet condensers are used, with the condensate being discharged to waste along with the cooling water. The only major electrical plant required in the generating station is a cooling-water pump. The thermodynamic efficiency of the power station at these low temperatures and pressures is about 10–15%. Thus large quantities of exhaust heat are available for local use or, alternatively, must be discharged as waste heat.

Heat from aquifers at lower temperatures is unsuitable for electricity generation but may be used for district heating or agricultural purposes. Several such aquifers with temperatures in the range 60–80°C exist.

Recent examples of district heating schemes exist in Southampton where the City Council is exploiting the heat from the Wessex Basin for space heating of Council office buildings. Several schemes are now operating in the Paris and Aquitaine Basins.

Power generation from geothermal aquifers began in 1904 in Lardarello, Italy, where installed capacity now exceeds 400 MW. Similar power-generation developments have taken place in China, El Salvador, Greece, Hawaii, Iceland, Indonesia, Japan, Kenya, Mexico, New Zealand, Nicaragua, the Philippines, Turkey, the CIS and the USA. Overall, it is estimated that some 8 GW of power is now being produced world-wide from geothermal aquifers.

At first sight geothermal energy would appear environmentally benign. However, no system of power generation is without some adverse environmental effect. Conventional geothermal power stations involve surface pipelines bringing steam from widely distributed bore holes to central power stations, and these can be unsightly and lead to visual intrusion. Geothermal aquifers incorporate gaseous components such as carbon dioxide, hydrogen sulphide, methane and radon. Such discharges need to be considered at the planning stage for new geothermal plant, otherwise environmental legislation may inhibit further expansion of the geothermal resource. Power generation from geothermal aquifers in volcanic areas can provide cheap electric power. Indeed, the generation costs are often quoted as being comparable with those of hydroelectric stations.

### 27.6.2 Hot dry rocks

The average thermal gradient near the surface of the earth is about 25°C/km. This temperature gradient is exceeded in some granites because of the local heat generated by the decay of radioactive elements. For example, in New Mexico granites have been identified with a thermal gradient of 50–60°C/km and in Cornwall gradients of 30–40°C/km have been measured in the Carmenellis granites.

In order to exploit these elevated subsurface temperatures for power generation, a temperature of greater than about 200°C is required. Thus wells of depths between 4 and 7 km are required. Current drilling technology sets a practical limit of about 6 km.

Two sets of field trials have been carried out in an attempt to exploit this enhanced heat source in granites. The first was conducted by the University of California at the Los Alamos Laboratories in New Mexico; the second was done by the Cambourne School of Mines at Rosemanowes quarry in Cornwall. The trials involve drilling a bore hole deep into the granite, fracturing the rock at the base of the bore hole using hydrostatic pressure and explosives, and then drilling a second bore hole to intercept the fractured zone. Water can then be circulated down one bore hole, permeate through the fractured zone, and hot water can rise to the surface through the second bore hole.

There are a number of practical difficulties associated with this scheme. The drilling of a second bore hole that is located sufficiently accurately to intercept the fractured zone is a problem in itself. Having created a circuit for water circulation, it has proved difficult to manage the flow of water such that a large surface area of hot rock is contacted by the circulating fluid. In practice, circulation through larger channels has tended to dominate and, therefore, depress the temperature rise of the circulating fluid. A further problem is the loss of circulating fluid due to subterranean leakage and the requirement for large volumes of cooling water for a process the overall thermodynamic efficiency of which is about 5%. Environmental problems from hot dry rocks include the release of radon gas, visual intrusion from cooling towers, and the stimulation of minor seismic events associated with the creation of the reservoir.

## 27.7 Biofuels

### 27.7.1 Introduction

Biomass and biofuels have no strict definition, but include agricultural residues, energy crops, municipal solid waste (MSW) and landfill gas.[26] It is convenient to differentiate between biofuels arising from agricultural sources and those which arise from human, urban and industrial processes. *Table 27.8* compares solid and gaseous fuels used for power generation according to this distinction[27] and *Table 27.9* lists relative energy content of the different materials used as fuel.

### 27.7.2 Biomass technologies

#### *27.7.2.1 Overview*

Energy can be recovered from biomass in a variety of ways including aerobic and anaerobic digestion, combustion with heat recovery and gasification/pyrolysis processes.

**Table 27.8** Renewable and waste fuel resources

| *Agricultural resources* | *Waste resources* |
|---|---|
| Sugar cane waste (bagasse) | Sewage Digester Gas (SDG) |
| Timber mill waste or sawdust | Landfill Gas (LFG) |
| Forestry residues | Mines gas |
| Short-rotation coppicing (SRC) | Coke-oven gas (COG) |
| Straw | Refinery and process plant flare/off gas |
| Rice husks and coffee husks | Stripped crude gas |
| Peanut and other nut shells | Municipal solid waste (MSW) |
| Palm oil and coconut residues | Hazardous and chemical waste |
| Meat and bone meal (MBM) | Hospital and clinical waste |
| Poultry litter | Sewage sludge |
| Livestock slurry | Vehicle tyres |

**Table 27.9** Calorific values for different materials used as fuels

| *Material used as fuel* | *Calorific value* (MJ/kg) |
|---|---|
| Coal | 23–32 |
| Fuel oil | 40–45 |
| Natural gas | 50–55 |
| Plastic | 27–34 |
| Municipal solid waste | 8.5–11 |
| Hospital and clinical waste | 17.5–22.5 |
| Chemical waste | 18.5–23 |
| Sewage sludge | 7–13 (depending on dryness) |
| Vehicle tyres | 32–40 |
| Sugar cane bagasse | 8–12.5 (depending on dryness) |
| Wood | 17–20 |
| Rice husks, Rice straw | 12–18 |
| Straw | 14–15.5 |
| Meat and bone meal | 20–28 (depending on fat content) |
| Poultry litter | 13–14 |

The main bio-energy conversion routes are represented in *Table 27.10* along with the principal products formed.

With the exception of sewage sludge and animal slurries most biomass materials are not in a form well suited to digestion processes. Commercially available digester plants have a relatively limited capacity, typically up to about 1 MW of biogas; hence for larger commercial applications the thermal treatment technologies for solid biomass are presently of more significance. Much work is underway at present, however, in the development of enzyme treatments to enable fermentation of cheap agricultural feedstock such as corn leaves and wheat straw into ethanol. A demonstration plant consuming 40 t of straw per day is reported as producing up to 4 m litres of ethanol/year. A car fuelled by a mixture containing 85% ethanol produces 91% less greenhouse gas emissions compared with petrol and so, given the present focus on reducing such emissions worldwide, this particular biomass transformation should feature more prominently in the future.

#### *27.7.2.2 Pyrolysis and gasification*

Pyrolysis is the thermal degradation of biomass in the absence of oxygen, but this may include partial gasification. Three products result: a solid char residue, gas and a complex, oxygenated hydrocarbon liquid containing water with the relative yields optimised according to the requirements and process control. The pyrolysis liquids can be burned in boilers, dual fuel diesel engine and turbines. Typically the pyrolysis gas is vented because of its low concentration of combustible gases, but high temperature pyrolysis produces a fuel gas that could be used in an engine or turbine.

Thermo-chemical gasification is the conversion by partial oxidation at elevated temperature of a carbonaceous feedstock such as biomass into a gas containing CO, $CO_2$, $H_2$, $CH_4$, trace amounts of higher hydrocarbons such as $C_2H_2$ and $C_2H_6$, water, nitrogen (if air is used as the oxidising agent) and various ash, oil and tar contaminants. The partial oxidation can be carried using air, oxygen, steam or a mixture of these. Air gasification produces a low heating value gas (up to 4–7 MJ/Nm$^3$) suitable for boiler, engine and turbine operation but not for pipeline transportation because of its low energy density; oxygen gasification produces a medium heating value gas (up to 10–18 MJ/Nm$^3$)

**Table 27.10** Bio-conversion processes and products

| *Process type* | *Process* | *Initial product* | *Final product* |
|---|---|---|---|
| Aqueous | Anaerobic digestion | Biogas (2 parts $CH_4$ to one part $CO_2$, 22–28 MJ/m$^3$) | Methane (38 MJ/m$^3$) |
| | Alcohol fermentation | | Ethanol (19 MJ/litre) |
| | Chemical reduction | | Oils (35–40 MJ/kg) |
| Dry thermo-chemical | Pyrolysis | | Pyrolytic oils (23–30 MJ/kg)<br>Gas (8–15 MJ/m$^3$)<br>Char (19–31.5 MJ/kg) |
| | Gasification | Low/Medium energy gas (7–15 MJ/m$^3$) | Methane (38 MJ/m$^3$)<br>Methanol (16.9 MJ/litre)<br>Ammonia<br>Electricity (3.6 MJ/kWh) |
| | Hydrogasification | | Methane (38 MJ/m$^3$)<br>Ethane (70.5 MJ/m$^3$)<br>Char (19–31.5 MJ/kg) |
| Direct combustion | of various fuels, e.g. wood chips (17–20 MJ/kg dry weight) | High pressure steam | High pressure steam<br>Electricity (3.6 MJ/kWh) |

suitable for limited pipeline distribution and as synthesis gas for conversion to methanol and gasoline.[34]

*27.7.2.3 Direct combustion*

The direct combustion of organic matter to produce steam or electricity is the most advanced of these conversion processes and, when carried out under controlled conditions is probably the most efficient. Waterwall incineration whereby water pipes within the walls of the incinerator are heated produces steam at high efficiencies for both electricity generation and CHP purposes. The moving grate combustion technology is well proven for coal firing and can accept many forms of biomass including relatively coarse solid materials, but has limited ability to handle wet sludges. Fluidised bed (FB) technology is also well established and proven for biomass combustion. It features intimate mixing of gases and high-temperature solids and allows very close control of temperature and reaction stoichiometry. The major advantages of fluidised beds are:

- Greater fuel flexibility—the ability to combust a variety of fuels with a wide ranging characteristics such as very-high ash fuels, high moisture fuels such as bark and sludges and high grade coal fuels.
- Lower temperature combustion without decrease in combustion efficiency thus inhibiting the formation of $NO_x$ emissions.
- The ability to fire fuels with low melting point ash.

There are two types of fluidised bed technology in common use in Europe, the bubbling fluidised bed (BFB) and the circulating fluidised bed (CFB). BFB units are available up to 100 MWe and have been proven on biomass and waste materials with homogeneous characteristics, especially lower capacity units starting from 5 MWth using well pre-prepared fuel. CFB units are available up to 400–600 MWe and have been demonstrated on up to seventy different fuel types both as single fuels and co-combusted providing increasingly cost-effective plant for combusting low-grade fuels and different wastes with low environmental impact.

## 27.7.3 Major biomass sources

*27.7.3.1 Short rotation coppicing and forestry residues*

Short rotation coppicing (SRC) consists of shrub willow planted at high density. At the end of the first year after planting the shoots are cut back to ground level to encourage a multi-stemmed form and the crop is then harvested on a three-year rotation in the winter. Fuel consumed in the harvesting represents a significant proportion of final electricity costs and care is needed to optimise fuel supply chains both from SRC and forestry residues. Studies[28,29] showed that for a base case transport distance of 56 km the energy ratio of energy content of delivered wood to energy expended in production was 26:1, with even a transport distance of 320 km showing a positive ratio of 8:1.

*27.7.3.2 Municipal solid waste*

Household waste (municipal solid waste) is processed by either recycling and/or composting or disposed of in landfill sites. For the UK the amount generated at present totals about 27 mt/y and increasing at 3% per year with some 85% of this total being sent for landfill (more than most other EC countries). The EC landfill directive will enforce major changes in landfill practices, however, requiring reductions in the biodegradable domestic waste sent to landfill by 2016 to be no more than 35% of its level in 1995. The development of more energy from waste schemes (EfW) is a virtual certainty.[35]

With the limitations imposed on the landfill option the major route for EfW is by mass burn incinerators. Gasification and pyrolysis of municipal solid waste has reached the large-scale pilot plant stage but their implementation is expected to be gradual and not to supersede conventional combustion processes.[35] Although the prime purpose of EfW plants is to dispose of waste, the typical plant size of 30–50 MWe output allows close integration into CHP schemes as is common in Austria, Denmark, France, Germany, Sweden, etc.

A further EC requirement is expressed in emission standards as shown in *Table 27.11*. All UK plants are being retrofitted and new ones designed to meet these requirements.

**Table 27.11** EC emission control requirements for energy from waste plant

| *Component* | *Emission to air in ng/Nm³—dioxins in ng/Nm³—dry gas 11% $O_2$* |
|---|---|
| Particulates | 10 |
| HCl | 10 |
| HF | 1 |
| $SO_2$ | 50 |
| $NO_x$ as $NO_2$ | 200 (plant >ς3 tph) |
| CO | 50 |
| VOC | 10 |
| Hg | 0.05 |
| Cd | 0.05 (Cd and TI) |
| 7 HM (heavy metal summation) | 0.5 |
| Dioxin I-TEQ ng/Nm³ | 0.1 |

*27.7.3.3 Landfill gas*

Landfill gas is the general name given to the gaseous products of bacterial decomposition of organic material within landfill sites. Such sites are constructed according to strict controls to limit their environmental impact with impermeable capping and internal lining, drainage control, in situ refuse compaction and ventilation. Organic matter decomposes aerobically in the presence of oxygen to produce carbon dioxide, but exclusion of air by means of the impermeable cap ensures anaerobic decomposition to produce water, and a flammable mixture of carbon dioxide and methane. The composition of landfill gas is variable depending on many factors, the rate of production depending on the rate of refuse decomposition with a half-life for the refuse-to-gas decomposition typically in the range of 3 to 10 years depending on the physical and chemical conditions within the waste, especially moisture levels.

It should be noted that not all landfill gas can be collected, but 25–50% is currently typical of a well-engineered site. A landfill site taking around 300 tonnes of degradable waste per day for ten years could theoretically generate as much as 4.5 billion cubic metres of gas over a period of forty years.

Spark ignited gas engines have provided the most popular means for the generation of electricity from landfill gas with the turbo-charged engine offering the best compromise in terms of capital cost, efficiency, performance and maintenance. Modern gas engines have a thermal efficiency of up to 39% and, with low compressor energy consumption, about 77% more electricity can be generated from the same volume of gas than by using gas turbines, which are also not very suitable for several reasons. Capital costs of a 1 MW installation (excluding gas collection and grid connection would be about £400 K (£400/kW) with engine maintenance about 0.75 p/kWh. The most cost-effective packages comprise 1–1.3 MW units and installing multiple units provides the flexibility to cope with the gas supply variations associated with landfill site operation.

## 27.8 Direct conversion

Some methods of extracting electrical energy from renewable sources do not rely on a heat stage, and the limitations of Carnot efficiency are avoided. Some other methods, still largely small scale and experimental, also eliminate machinery, relying instead on direct conversion processes. Like solar cells, the direct conversion processes described below produce electricity at low direct voltage; many units need to be interconnected and coupled to inverter systems to give a.c. output. Direct conversion processes generally need to be operated at high temperatures, and difficulties are encountered in finding suitable materials to withstand such temperatures over a long lifetime.

### 27.8.1 Thermoelectric generators

*27.8.1.1 Principles*

If two dissimilar materials are joined in a loop with the two junctions maintained at different temperatures, an e.m.f. $E = \alpha\theta$ is set up around the loop, where $\theta$ is the temperature difference and $\alpha$ is the Seebeck coefficient (itself depending to some extent on temperature). The phenomenon, long used in thermocouples, enables generators with semiconductor junctions to supply up to 5 kW for radionavigation beacons and satellites. A useful figure of merit is $Z = \alpha^2\sigma/K$, where $\sigma$ is the electrical conductivity (which should be high, to reduce $I^2R$ loss) and $K$ is the thermal conductivity (which should be low, to limit heat transfer between junctions).

If the thermoelectric generator works between absolute temperatures $T_1$ and $T_2$, the efficiency as a fraction of the Carnot efficiency is

$$\eta = [(1 + ZT)^{1/2} - 1]/[(1 + ZT)^{1/2} + T_2/T_1]$$

where $T = \frac{1}{2}(T_1 + T_2)$. Thus the efficiency depends on the product $ZT$, which is a convenient assessment for possible thermoelectric materials. In practice, no single combination maintains a high $ZT$ over a wide temperature range: most practical designs use a series of stages with n- and p-type semiconductor junctions that have a high $ZT$ over their relevant temperature differences.

Taking into account mechanical characteristics, stability under operating conditions and ease of fabrication, bismuth telluride appears to be one of the most suitable materials; it can be alloyed with such materials as bismuth selenide, antimony telluride, lead selenide and tin telluride to give improved properties, is suitable for temperatures up to about 180°C, and can give efficiencies up to about 5%. A silicon–germanium alloy with phosphorus and boron impurities can be used up to 1000°C and might give efficiencies up to 10%.

*27.8.1.2 Practical developments*

A typical thermoelectric couple could be designed to give about 0.1 V and 2 A (i.e. about 0.2 W), so that a 10 W device suitable for a navigational beacon or unattended weather station would require about 50 couples in series. Various methods have been used to provide a source of heat for the hot junction. These include small oil or gas burners, isotopic heating and solar radiation. Although some progress has been made in developing suitable materials, theoretical studies seem to show that the scope for improvement in $ZT$ values is rather limited. For this reason, interest in thermoelectric devices has declined over the last decade.

### 27.8.2 Thermionic generators

In its simplest form the thermionic converter comprises a heated cathode (electron emitter) and an anode (electron collector) separated in a vacuum, the electrical output circuit being connected between the two. Heat supplied to the cathode raises the energy of its electrons to a level enabling them to escape from the surface and flow to the anode: at the anode their energy appears partially as heat (removed by cooling) and partially as electrical energy delivered to the circuit. Although the distance between anode and cathode is only about 1 mm, the negative space charge with such an arrangement hinders the passage of the electrons and must be reduced—e.g. by introducing positive ions into the inter-electrode space, caesium vapour being a valuable source of such ions. Anode materials should have a low work function (e.g. barium oxide and strontium oxide), while that of the cathode should be considerably higher, tungsten impregnated with a barium compound being a suitable material. With these materials temperatures up to 2000°C will be needed to secure, for the generator itself, efficiencies of 30–35%, although higher overall efficiency can be obtained by using the heat from the coolant. Electrical outputs of about 6 W/cm$^2$ of anode surface have been suggested.

Developments of thermionic generators using radioactive isotopes as the heat source have taken place for space applications. Thermionic devices, in general, do not appear to offer significant potential as power sources.

### 27.8.3 Magnetohydrodynamic generators

In the magnetohydrodynamic generator a partially conducting gas is heated by a fuel fired or nuclear reactor, allowed to expand through a nozzle to convert the heat energy to kinetic energy, and then passed between the poles of an electromagnet, the field of which converts some of the kinetic energy to electrical energy which can be collected from electrodes situated in the gas channel. The generator is thus not quite a direct heat-to-electricity device, as are the thermoelectric and thermionic devices, for there is an intermediate kinetic energy stage; also, largely owing to the power required for the electromagnets and other losses, it is unlikely to give a useful output unless built in sizes of 50 MW or more.

Provided that the gas is conducting and moving at right angles to the magnetic field, an e.m.f. will be set up at right angles to the direction of motion and of the magnetic field, being proportional to the velocity of the gas and to the magnetic flux density. This e.m.f. can be collected from suitable electrodes located in the gas stream and can supply power to an external circuit. The power output is proportional to the square of the velocity, to the square of the flux density and to the conductivity of the gas between the electrodes.

The field density should therefore be as high as possible, making superconducting magnets to give fields of 4–5 T, a great advantage over conventional magnets. Gas velocities up to 1000 m/s are practicable. The electrical conductivity of gases even at temperatures of 2000–3000°C is too low to give practicable powers. Ionisation must therefore be artificially increased by *seeding* the gas with an easily ionisable element such as caesium or potassium. Either must be recycled for economical operation, but caesium is so expensive and corrosive that a closed-cycle system is essential.

The possibility of using a liquid metal, sodium or potassium, is being investigated; such a fluid would have a much higher electrical conductivity but a lower velocity, the major problem being that of producing a high velocity with sufficient liquid density to give an adequate conductivity.

With gaseous conductors a complication is introduced by the Hall effect—i.e. by the fact that the current flow between the electrodes is not in the same direction as the field: the Hall angle may reach 80°, increasing with low pressures, high magnetic fields and high electron mobilities. The resulting axial component of current flow leads to inefficiency. To counter the Hall effect the number and configuration of the electrodes is more complex. In the Faraday generator a single pair of electrodes, or several pairs connected to separate load circuits, are used, but these arrangements are not appropriate for Hall angles of more than 45°. In the Hall generator use is made of the axial component by a more complex electrode arrangement in which current is collected from axially spaced electrodes; Hall angles up to 80° are appropriate with this type.

Extensive programmes of work are in progress in the USA and the CIS to develop the open-cycle fossil fired system. In this the fuel-combustion products at temperatures over 2000°C, achieved by preheating the combustion air, are seeded with potassium carbonate and passed through a magnetohydrodynamic duct. The waste gases are then used to heat a conventional steam cycle. The magnetohydrodynamic process is therefore a topping unit increasing the overall efficiency of power generation to about 45% and potentially over 50%. The potassium carbonate also combines with the sulphur in the coal to form potassium sulphate which is removed from the boiler with the ash, the sulphur being removed and the potassium recycled. The system therefore has an added advantage where sulphur emissions must be controlled, as is required in the USA. The main problems are the development and cost of a suitable gas duct and electrode system to withstand the high temperature and corrosive effect of the gas for long periods, and the effective recovery and recycling of the seed material. In addition, large air heaters and superconducting magnets are needed. The CIS has a 20 MW prototype station which has operated continuously for up to 250 h at 10 MW on natural gas. A larger unit is proposed in which the duct-life problem is avoided by having two ducts which are used alternately and regularly refurbished. The US programme is also being directed towards the evaluation of large-scale components for open-cycle magnetohydrodynamic generation, but using coal as the fuel.

## 27.9 Fuel cells[36–40]

### 27.9.1 Introduction

Fuel cells are energy conversion devices, which by combining hydrogen and oxygen into water convert chemical energy into electricity and heat. A fuel cell works much like a battery. In both batteries and fuel cells two electrodes, an anode and a cathode, are separated by an electrolyte. Whereas a storage battery contains all the substances in the electrochemical oxidation-reduction reactions involved and has, therefore, a limited capacity, a fuel cell is supplied with its reactants externally and operates continuously as long as it is supplied with fuel.[36,37]

### 27.9.2 Fuel cell types

There are five basic types of fuel cell being commercially developed, a classification being based on the electrolytes used. Low temperature types include the alkaline fuel cell (AFC) and the solid polymer fuel cell (SPFC), to which belong the proton exchange membrane fuel cell (PEMFC) and the direct methanol fuel cell (DMFC), the medium temperature type is the phosphoric acid fuel cell (PAFC) and the two high temperature types are the molten carbonate fuel cell (MCFC) and the solid oxide fuel cell (SOFC). An idealised schematic diagram illustrating the structure, electron and ion flow for the various types of fuel cell is shown in *Figure 27.5*.

Phosphoric acid (PAFC) and proton exchange (PEMFC) fuel cells both use acid electrolytes, alkaline (AFC) and molten carbonate (MCFC) fuel cells use liquid alkaline-based electrolytes while solid oxide (SOFC) fuel cells use a zirconia-based ceramic. The direction of the ion flow depends on whether the ion is positively or negatively charged and also determines the site of water formation and subsequent removal. *Table 27.12* summarises the different characteristics of these fuel cells

*Alkaline fuel cells (AFC)* The application of AFCs in space has been especially noteworthy. They are ideally suited to closed environments containing their own supplies of hydrogen and oxygen and have also been demonstrated in a variety of automotive applications. AFC performance is particularly sensitive to contaminants in the gas supplies, notably carbon dioxide, which reacts with the electrolyte to form a carbonate and reduces the conductivity. With the chemical reaction occurring at the cathode and the low operating temperature the start-up time of the AFC is very fast and the cell yields high power generation efficiencies as seen in *Table 27.12*.

*Proton exchange membrane fuel cells (PEMFC)* The low operating temperatures and the solid electrolyte—an acid-based ion conducting plastic membrane—also make PEMFCs suited to a wide array of uses from low and medium to high power applications. Such a list would include power tools, compressors, recreational applications in camping and boats, heat and electricity to dwellings and electricity to commercial buildings, schools and hospitals. They are most widely known at present for their potential in automotive applications where much evaluation is underway. The low temperature electrolyte requires platinum as the catalyst applied to either side of the membrane to accelerate the dissociation of hydrogen and oxygen. The hydrogen fuel stream should contain less than 10 ppm of carbon monoxide, preferably none, because carbon monoxide will bond to the platinum and poison its catalytic property leading to significantly degradation in the cell performance.

*Direct methanol fuel cell (DMFC)* This cell is similar to the PEMFC except that hydrogen is extracted from a methanol/water solution. This gives it an advantage inasmuch as the hydrogen is extracted by the catalyst and not by the addition of complex reforming plant. In addition

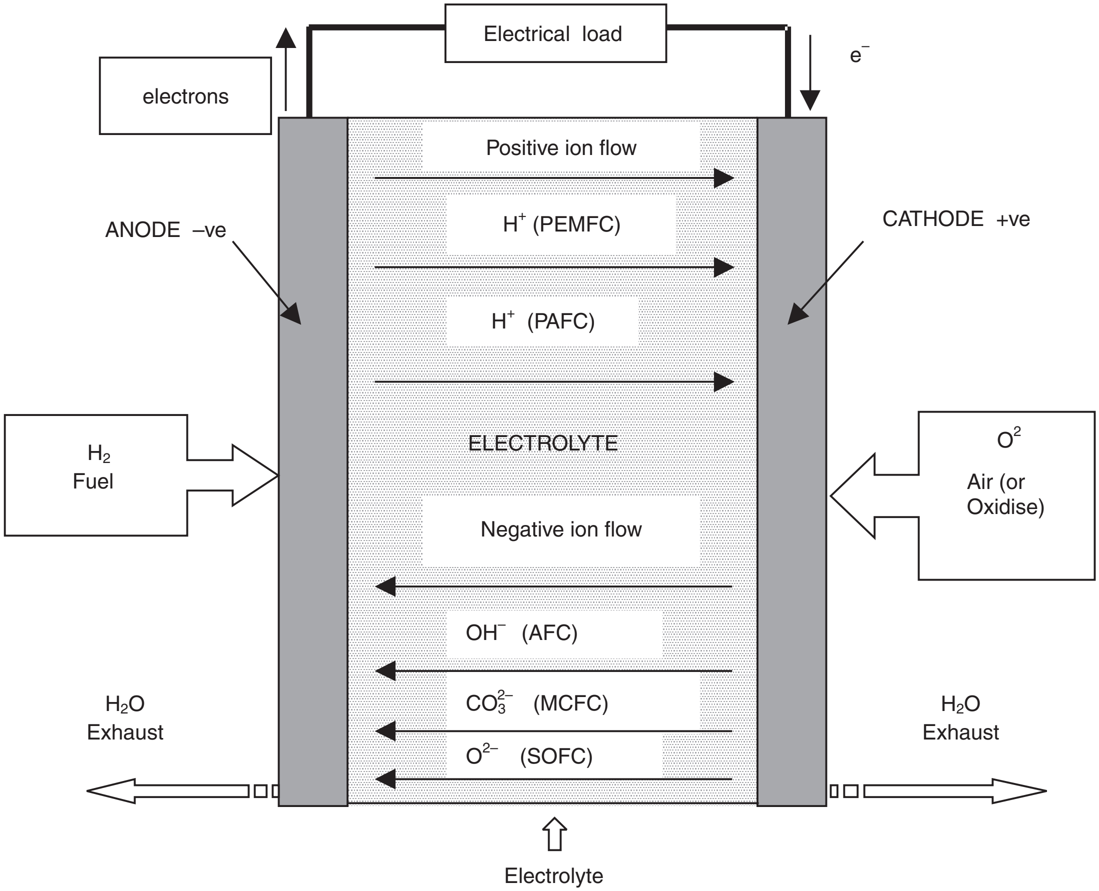


**Figure 27.5** Principle of fuel cell operation

the use of methanol would not require such major forecourt engineering for automotive purposes, as would the input of pure of hydrogen. The initial markets for DMFCs are considered to be in the small and medium power applications such as occupied by batteries in consumer and military electronic products. The power to weight ration is theoretically of the order of 10:1 compared with batteries. The main outstanding problem is the 'cross-over' of methanol from the anode to the cathode through the membrane drastically reducing the cell performance. In addition significantly more platinum is required at the anode than in the PEMFC to catalyse the water/methanol mix.

*Phosphoric acid fuel cell (PAFC)* These fuel cells have given much durable service over many years with a very stable electrolyte in medium to high power stationary applications. Typically 200 kW units are found in hospitals, schools, hotels and various military installations. With its higher temperature carbon monoxide poisoning is not such a severe problem as in the PEMFCs, but with poor ionic conduction this comparatively large and weighty cell technology appears to be relatively expensive.

*Molten carbonate fuel cell (MCFC)* Multi-megawatt plants have been demonstrated with obvious applications in commercial buildings, especially those requiring high quality heat such as in commercial buildings, hospitals and hotels. Developments include cells for use in natural gas and coal-based power plants in heavy industries. The high operating temperatures allow the use of fuels such as natural gas and coal gas without the need of noble metal catalysts and allow the fuel to be internally reformed without the need of complex reforming equipment. The quality of the heat allows for the possibility of higher efficiencies when coupled to CHP or combined cycle plant.

*Solid oxide fuel cell (SOFC)* Here the biggest problem in the development of these cells is coping with the high operating temperatures above 850°C where significant material problems occur. Below this temperature ionic conduction is a problem and the cell's performance deteriorates rapidly. Designs and demonstrations are being carried out to supply a wide variety of stationary needs from a few kilowatts to multi-megawatt industrial and power system plants as well as automotive power units. The high temperatures confer the same advantages onto this cell as for the MCFC design with the high temperatures adding further to CHP and combined cycle plants. As a completely solid state device, however, the management problems inherent in liquid electrolyte designs are avoided and, in principle, there are no constraints on cell configuration allowing flexibility in design.

**Table 27.12** Fuel cell types and characteristics

| *Type* | *AFC* | *PEMFC* | *DMFC* | *PAFC* | *MCFC* | *SOFC* |
|---|---|---|---|---|---|---|
| *Electrolyte* | Aqueous potassium hydroxide (30–40%) | Sulphonated organic polymer (hydrated during operation) | Sulphonated organic polymer (hydrated during operation) | Phosphoric acid | Molten Lithium/ Sodium/ Potassium carbonate | Yttria-stabilised Zirconia |
| Operating Temp.°C | 60–90°C | 70–100°C | 90°C | 150–220°C | 600–700°C | 650–1000°C |
| Anode | Nickel (Ni) or precious metal | Platinum (Pt) | Platinum–Ruthenium (Pt, Ru) | Platinum (Pt) | Nickel/ Chromium oxide | Nickel/Yttria-stabilised Zirconia |
| Cathode | Platinum (Pt) or lithiated NiO | Platinum (Pt) | Platinum–Ruthenium (Pt, Ru) | Platinum (Pt) | Nickel oxide (NiO) | Strontium (Sr) doped Lanthanum manganite |
| Charge Carrier | $OH^{-\Leftarrow}$ | $H^{+\Leftarrow}$ | $H^{+\Leftarrow}$ | $H^{+\Leftarrow}$ | $CO_3^{=\Leftarrow}$ | $O^{=\Leftarrow}$ |
| Anode reaction | $2H_2 + 4OH^{-\Leftarrow} \rightarrow 4H_2O + 4e^{-\Leftarrow}$ | $2H_2 \rightarrow \Leftarrow 4H^+ + 4e^{-\Leftarrow}$ | $CH_3OH + \Leftarrow H_2O \rightarrow CO_2 + 6H^+ + 6e^{-\Leftarrow}$ | $2H_2 \rightarrow \Leftarrow 4H^+ + 4e^{-\Leftarrow}$ | $2H_2 + 2CO_3^{=\Leftarrow} \rightarrow 2H_2O + \Leftarrow 2CO_2 + 4e^{-\Leftarrow}$ | $2H_2 + 2O^{=\Leftarrow} \rightarrow 2H_2O + 4e^{-\Leftarrow}$ |
| Cathode reaction | $O_2 + 2H_2O + 4e^- \rightarrow 4OH^{-\Leftarrow}$ | $O_2 + 4H^+ + \Leftarrow 4e^- \rightarrow 2H_2O$ | $3/2\ O_2 + 6H^{+\Leftarrow} + 6e^- \rightarrow \Leftarrow 3H_2O$ | $O_2 + 4H^+ + \Leftarrow 4e^- \rightarrow 2H_2O$ | $O_2 + 2CO_2 + 4e^- \rightarrow 2\ CO_3^{=\Leftarrow}$ | $O_2 + 4e^- \rightarrow 2O^{=\Leftarrow}$ |
| Heat application | Space $+\Leftarrow$ Water | Space $+\Leftarrow$ Water | Space $+\Leftarrow$ Water | Space $+\Leftarrow$ Water | Combined cycle, CHP | Combined cycle, CHP |
| Electrical efficiency % | 60–70 | 40–45 | 30–35 | 40–45 | 50–60 | 50–60 |
| Fuel sources | $H_2$ removal of $CO_2$ from both gas streams necessary | $H_2$ reformate with less than 10 ppm CO | Water/ Methanol Solution | $H_2$ reformate | $H_2$, CO, Natural gas | $H_2$, CO, Natural gas |

### 27.9.3 Fuel cell structure

The theoretical limit on voltage developed by a single cell is about 1.23 V with typical operation being at about 0.7 V. Current (d.c.) delivered is approximately 0.5 amps/cm$^2$ of cell surface area giving an output power of about 0.35 watts/cm$^2$. To generate more power the cells are connected together in stacks. *Figure 27.6* shows the structure of a phosphoric acid fuel cell stack together with the flow of gas. These fuel cells can be divided into two groups according to their structure: ribbed separators or ribbed electrodes. A thin layer, or matrix electrode, containing phosphoric acid is sandwiched between the electrodes. The electrodes, or the layers in contact with them, are ribbed to provide a manifold, which ensures that each cell is fed uniformly with air and fuel. The cells can be stacked horizontally or vertically and held together by endplates. The structure is much the same for all types of fuel cell.

### 27.9.4 Fuel cell plant

A complete fuel cell plant comprises a fuel delivery system, a stack, various controls over the plant operation and output power conditioning equipment. The fuel delivery system can range from a simple flow control unit to a fuel pre-processing unit. In practice hydrogen always occurs in combination with other elements. It is necessary, therefore, to produce it either by electrolysis in the case of water or by separation in a reformer if a hydrocarbon fuel is used as a primary source. A fuel cell system, which includes a fuel reformer, can utilise, in principle, the hydrogen from any hydrocarbon fuel from natural gas to methanol. The two primary types of reformers being developed for transportation are steam reformers and partial oxidation reformers. Steam reformers have higher efficiency but partial oxidation reformers are simpler.

Plant control includes water management control and appropriate temperature control. As exhaust product water is seen as providing a potentially important added benefit in fuel cell operation in future, given concerns about the adequate local supplies of pure water for human consumption and industrial purposes. With regard to temperature control, a preheating stage particularly for high temperature fuel cells may be required for start-up. Heat exchangers are required to ensure the reactants enter the cells at appropriate temperatures for operation, again a particularly important requirement for high temperature cells. The flow rate of the oxidant generally controls the stack temperature.

Finally the power conditioning equipment converts the electricity generated, which is in the form of direct current, into the form required for use, usually alternating current at specified voltage and frequency.

*Figure 27.7* illustrates the structure of a fuel cell plant with heat reformer to convert fossil fuel such as natural gas or methanol into hydrogen, or a hydrogen rich gas for supply to the cells and *Table 27.13* provides an outline specification of a 2.8 kW alkaline fuel cell.

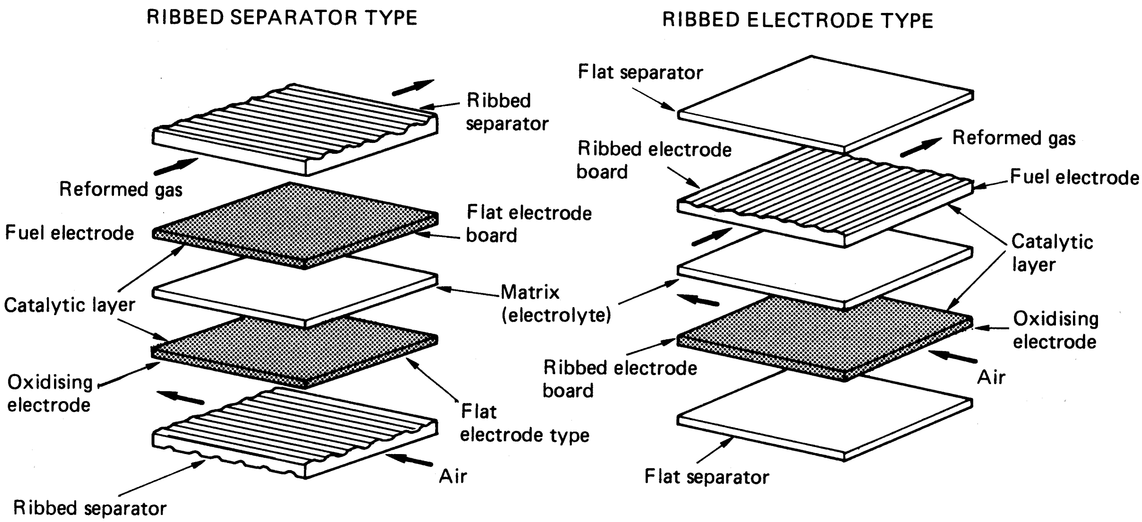


**Figure 27.6** Stack cell structure for a phosphoric acid fuel cell

### 27.9.5 Regenerative fuel cells[38–40]

Fuel cell systems incorporating the collection of the water exhaust, its dissociation by electrolysis using an external source of electricity with storage and subsequent use of the hydrogen and oxygen produced, form a regenerative system. Such systems, for example belonging to the PEM group, could be independent of established fuel/energy infrastructures. The pure forms of the gases would be a further benefit in cells susceptible to carbon monoxide or carbon dioxide. Applications are seen initially in uninterruptible power supplies and in remote power requirements.

A different type of regenerative fuel cell has been developed known as the Regenysis® system which could also be considered as a flow cell type of battery using fuel cell technology. Its chemistry is not based on combining hydrogen and oxygen into water and converting chemical energy into electricity and heat, but instead stores or releases energy by means of a reversible electrochemical reaction between two electrolyte solutions. The electrolytes are the respective salts sodium bromide and a sodium polysulphide and are physically separated by a permeable ion-exchange membrane.

The simplified overall reaction for the cell is given by

$$\underset{\text{uncharged state}}{3\,NaBr + Na_2S_4} \Longleftrightarrow \underset{\text{charged state}}{2Na_2S_2 + NaBr_3}$$

The electrolytes are pumped through two separate electrolyte circuits and transformed electrochemically inside the cell. The charge capacity is limited by the quantities of electrolytes stored in external tanks from which they flow into and out of the cell through separate manifolds via a controlled pumping supply plant. The input of electrical energy from an external source charges the cell with a cation selective membrane preventing the sulphur anions reacting

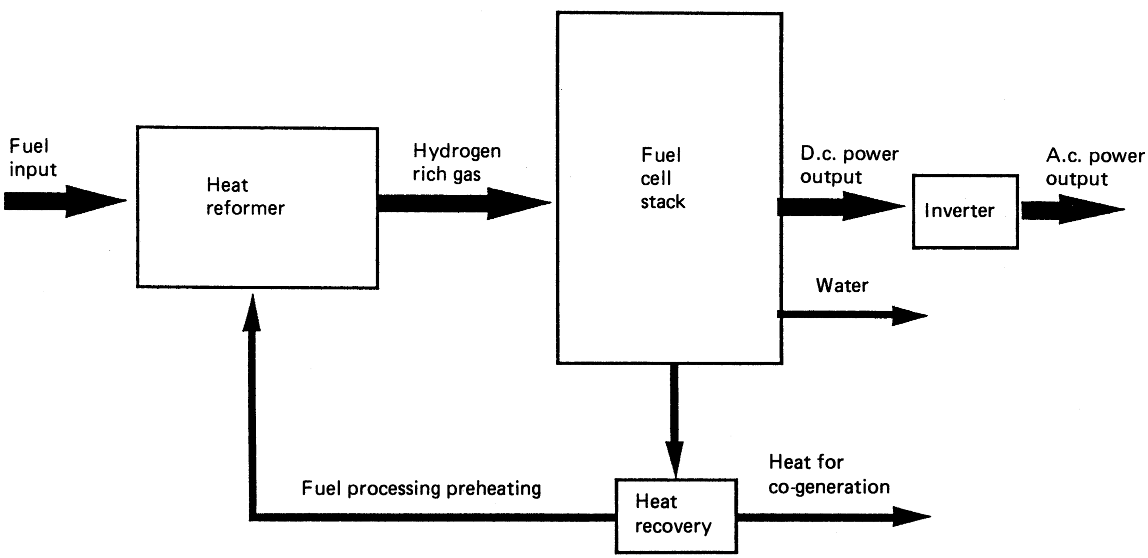


**Figure 27.7** Fuel cell power-generation system

**Table 27.13** Specification of a low power alkaline fuel cell

| | | | |
|---|---|---|---|
| *Stack configuration* | | *Nominal operating conditions* | |
| 8 modules connected in series | | Reaction temperature | 70°C |
| *Nominal dimensions* | | Reaction pressure | Atmospheric |
| Length | 895 mm | Hydrogen quality | Industrial grade (99.95%) |
| Width | 250 mm | Air quality | Max. 50 ppm $CO_2$ |
| Height | 310 mm | Nitrogen quality | Industrial grade (99.998%) |
| Weight (excluding electrolyte) | 38 kg | Electrolyte | Potassium hydroxide |
| Weight (including electrolyte) | 48 kg | Electrolyte concentration | 6.6 mol/l (30% by weight) |
| Volume | 69 litres | Hydrogen supply pressure | Ambient + 40 mbar |
| | | Air supply pressure | Ambient + 40 mbar |
| *Environmental operating conditions* | | Electrolyte supply pressure | Ambient + 60 mbar |
| Temperature range | − 10°C to 55°C | Stack lifetime (10% degradation in output power) | 5000 h |
| Humidity range | 50% to 90% | | |
| Pressure range | Ambient ±10% | *Fluid flows at full power* | |
| | | Hydrogen consumption | 2.15 $Nm^3$/h |
| *Electrical output at nominal operating conditions* | | Air consumption | 22.5 $Nm^3$/h |
| Open circuit voltage | Min. 44 Vdc +10% | Nitrogen consumption | 0.16 $Nm^3$ per on/off cycle |
| Nominal voltage | 32 Vdc ±5% | Electrolyte flow rate | 400 l/h at ΔT of 2.5°C |
| Nominal current | 90 A ±5% | Max. water production rate | 1.93 l/h |
| Nominal power | 2800 W ±5% | | |
| Maximum allowable current | 100 A | *Electrical efficiency* | 45%–55% (subject to load, excluding heat recovery) |

directly with the bromine separating the solutions. Electrical balance is achieved by the transport of the sodium ions across the membrane.

The overall electrical efficiency of such a system comprising cell, control system and power conversion unit is about 65%, being restricted by membrane performance in transferring the sodium ion $Na^+$, but with a target efficiency of 80%. Such a fuel cell operates at ambient temperatures and pressures and is, therefore, not suitable for CHP schemes. One design comprising one hundred 100 kW stacks or modules provides 120 MWh of energy storage capable of being released at a rate of 12 MW for 10 h with a peak output of 14.75 MW. In common with all electrochemical systems, maximum efficiency is achieved below the maximum power rating. Power response is fast with zero to full discharge being achieved in 10–15 ms, being limited by the performance of the power conversion unit.

## 27.10 Heat pumps

### 27.10.1 Introduction

Heat pumping is the use of a thermodynamic cycle to extract heat from a lower temperature source and supply it to a higher temperature sink where it is useful. In doing so, the purchased energy needed to drive the cycle is less than that usefully supplied. The ratio between useful heat delivered and the energy purchased is the coefficient of performance (COP). It should always be greater than unity.

Thermodynamic cycles have been well developed over the last century for refrigeration, but it is only in recent years that the heating application has developed. They were first applied in the USA where the coastal regions required air conditioned cooling in summer and space heating in winter.[41–47]

The energy crisis in 1974 produced a resurgence in interest in heat pumps, particularly in Japan, France, Germany and Scandinavia. The high capital cost of the units and the stabilisation of fuel prices led to a reduction in sales until the environmental problems of $CO_2$ were recognised in the 1980s. This provoked a renewed interest and led to newer more reliable, quieter compressors and more efficient cycles. The Japanese are leading this quiet revolution. The applications have widened from simple heat pumping in winter to industrial heat recovery and dehumidification.

### 27.10.2 Thermodynamics

The ideal thermodynamic cycle for heat pumps, developed by Carnot, assumes a perfect working fluid operating in perfect conditions:

$$\text{Ideal COP} = \frac{T_{\text{hot}}}{T_{\text{hot}} - T_{\text{cold}}}$$

where the heat is extracted from a cold source and supplied to a hot sink. The temperatures are absolute temperature (i.e. degrees Celsius + 273).

This ideal cycle shows that the usefulness of a heat pump cycle depends mainly on the temperature difference between the heat source and the heat sink. The heat pump performance improves as this temperature difference narrows. The heat pump also improves slightly with increasing temperature.

$$\text{COP} = \frac{\text{Heat out}}{\text{Compressor} + \text{Fan energy in}}$$

In practice, with real fluids and real equipment the best performance is obtained from the vapour compression cycle, which achieves about one-third of the ideal Carnot efficiency (see *Figure 27.8*).

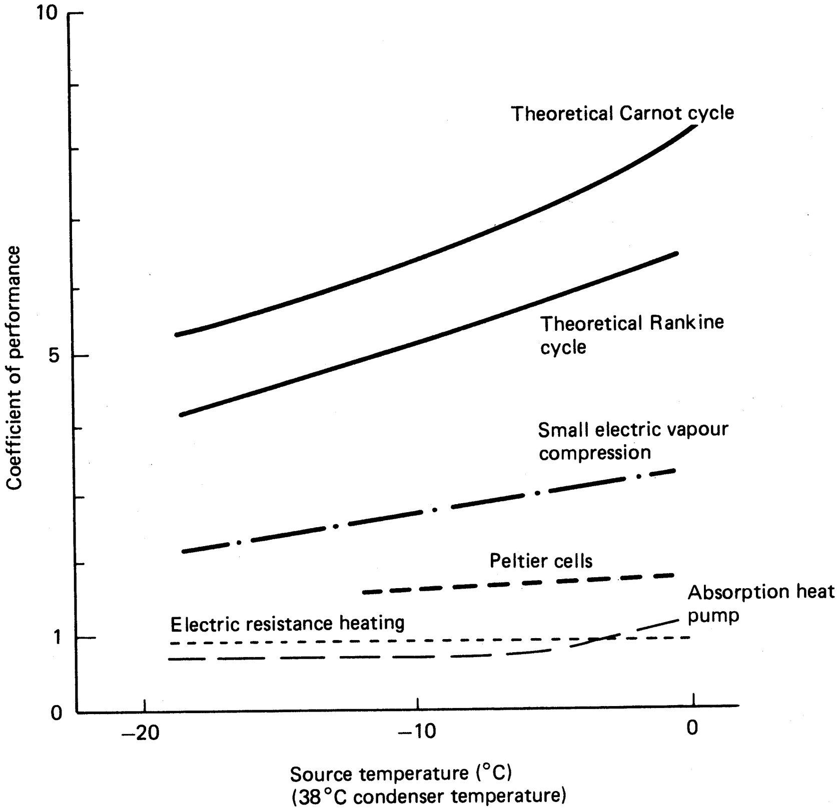


**Figure 27.8** Coefficients of performance in theory and practice

### 27.10.3 Practical cycles

The four basic cycles are described below.

#### *27.10.3.1 Air cycle*

When air is compressed, it becomes warmer. Heat can be extracted and the cooled pressurised air expanded down to its original pressure. The expander can be a turbine which drives the compressor. This open cycle can be used for heating buildings. Unfortunately, the equipment is very bulky and its efficiency is very sensitive to the inefficiencies of both the compressor and the expander.[48,49] It is not commercially attractive except for special applications where compressed air is readily available, such as aircraft air conditioning.

#### *27.10.3.2 Vapour compression cycle*

The vapour compression cycle relies on the condensation temperature increasing with increase in pressure. A vapour from the evaporator when compressed will condense at a higher temperature, corresponding to the new higher pressure. Successful working fluids must have a high latent heat of condensation so that the bulk of the heat can be extracted at the highest possible temperature. This principle applies to all conventional heat pumps (*Figure 27.9*).

The change in pressure between the evaporator and the condenser can be created by any mechanically driven compressor. Almost all the equipment in use is mechanically driven and electric motors are the driving units. They are favoured because of their cost, simplicity, silence, efficiency, long life and reliability. However, there is an increasing use of fossil-fuel-driven engines because the waste heat from such an engine can often be incorporated into the heating scheme[50] (*Figure 27.10*).

The selection of heat pump working fluids is complex, but a critical factor is the range of permissible condensing temperatures. The upper-temperature limits depend on the compressor. Piston compressors, where the lubricating oil is in

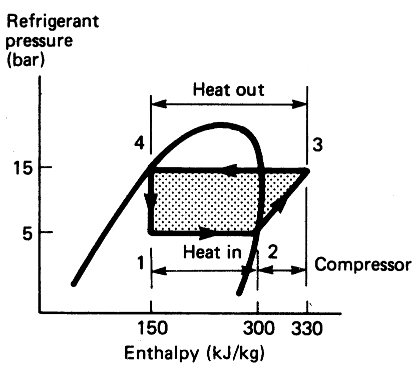


**Figure 27.9** The vapour compression cycle (R22). From 1 to 2 the refrigerant vapour absorbs heat. From 2 to 3 the compressor compresses the gas. From 3 to 4 the gas is condensed and its latent heat released. From 4 to 1 the liquid expands to a vapour at the lower pressure

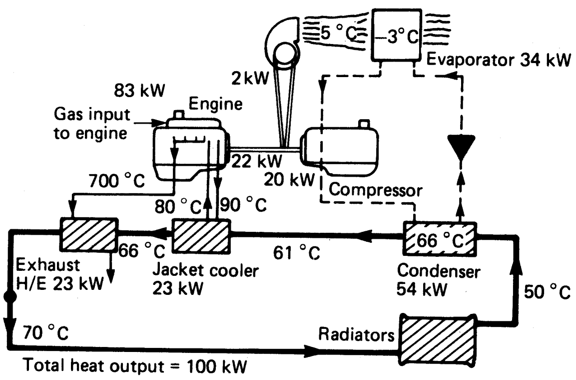


**Figure 27.10** A gas engine driven air-to-water heat pump with heat recovery from the engine (coefficient of performance 2.7)

intimate contact with the working fluid, are constrained by oil degradation. Dry compressors, where the bearings are sealed from the working fluid, can operate at higher temperatures. However, the chemical and physical stability of the working fluid itself then provides the working-temperature limits.[51,52]

In 1985 environmentalists discovered that certain refrigerants are attacking the protective stratospheric ozone layer around the earth and destroying it. These refrigerants are the chlorofluorocarbons (CFCs). Government action in Montreal in 1985 produced the first international agreement on restrictions necessary to protect the environment.[53] The two popular fluids R11 and R12 were amongst the most damaging chemicals and are progressively being phased out. Consumption in 1998 was down to 50% of the production in 1986. New ozone friendly refrigerants, in particular R134a, as a substitute for R12, are being developed.[54,55] A range of operating temperatures for different working fluids is illustrated in *Figure 27.11*.

Present-day refrigerants are normally pure single halocarbon compounds. They have simple properties and boil and condense at constant temperatures. They are azeotropic. Non-azeotropic mixtures have advantages in heat transfer and can be used to optimise cycle efficiencies. An illustrative enthalpy diagram is shown in *Figure 27.12*.[56]

This concept is now being used to control externally the refrigerant in the heat pump circuit by storing the refrigerant in a heated rectifier.[57–59] The composition of the refrigerant in the circuit is then controlled by the rectifier temperature (*Figure 27.13*).

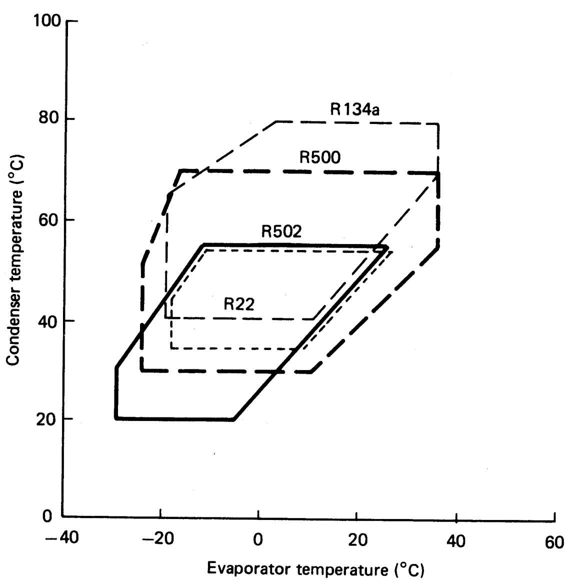


**Figure 27.11** The operating-temperature range for different working fluids

### *27.10.3.3 Absorption heat pump*

The absorption cycle works on the same principle as the vapour compression cycle, except that the change in pressure is brought about by adding heat to a solution and releasing the absorbed refrigerant at a higher temperature and pressure.[45,60] The circuit is illustrated in *Figure 27.14*.

The refrigerant leaving the evaporator is physically absorbed in the absorbent, releasing heat. In this mixture the evaporator pressure becomes the partial pressure of the refrigerant in solution. This mixture is then brought up to the pressure of the generator by a liquid solution pump. Heat is applied to the generator and part of the refrigerant boils off and passes to the condenser when heat is released. The refrigerant then passes through an expansion valve to the evaporator. Meanwhile, within the generator, the solution, now depleted of much of the refrigerant, is brought down to the absorber pressure to restart the cycle.

The working fluids are usually ammonia and water or lithium bromide and water. Coefficients of performance are typically 1.2–1.4 on full load.[59] While this is modest, such units are usually gas fired with efficiencies of around 60–70%. The absorption cycle is, therefore, able to double the effectiveness of such energy use.

Part-load performance falls rapidly below 40% heating duty (*Figure 27.15*) and, therefore, the heat pump units are

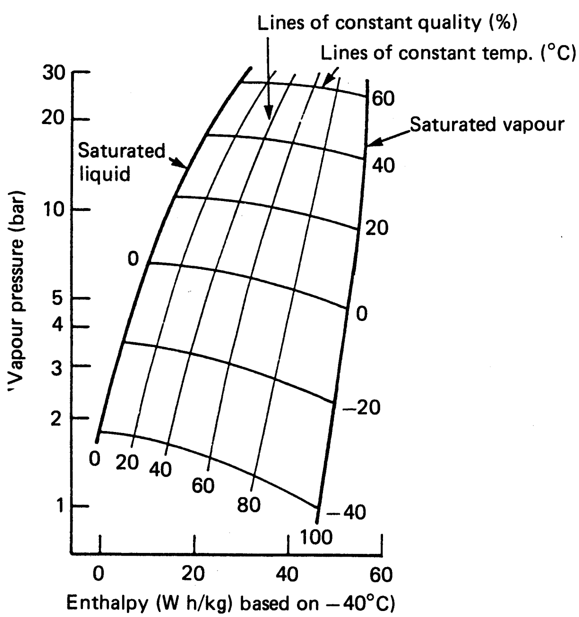


**Figure 27.12** Non-azeotropic mixtures do not boil and condense at constant temperature. The enthalpy diagram illustrates the saturated liquid line (bubble point) and the saturated vapour line (dew-point) of a 70%/30% mixture of R13B1/R152A

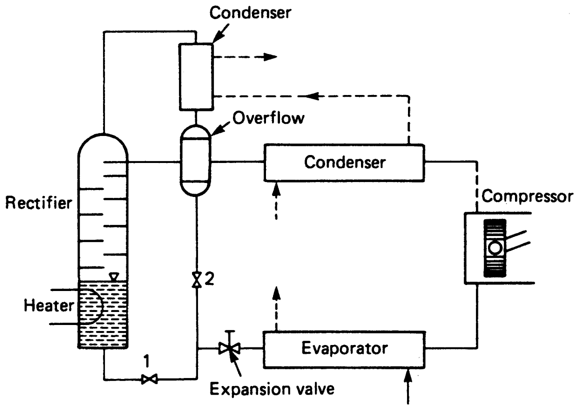


**Figure 27.13** The refrigerant composition can be varied at will with a heated rectifier in the non-azeotropic refrigerant circuit

normally underrated for the design condition so that they spend most of their time at full load. The performance characteristics are much less sensitive to source temperature than vapour compression cycles[61] (*Figure 27.16*).

#### 27.10.3.4 Thermoelectric heat pump: Peltier device

When a direct electric current passes round a circuit incorporating two different metals, one junction of the two metals is heated and the other cooled.[62,63] To be effective, these Peltier couples must have a high thermoelectric coefficient $\alpha$, a low thermal conductivity $\kappa$, and low electrical resistivity $\rho$. The high thermal conductivity of metals normally makes the units very inefficient (coefficient of performance 1.01). However, recent progress in semiconductors has improved $\alpha$, enabling much more effective units to be made.

The Peltier effectiveness ($z$) is given be

$$z = \frac{\alpha^2}{\kappa\rho\varsigma}$$

Present-day materials have $z = 0.003/\kappa$.

The overall performance of such devices is still short of that achieved by vapour compression cycles but the small size, reliability and ease of making low-capacity modules gives them a special market. A typical module layout is illustrated in *Figure 27.17*.

### 27.10.4 Scale

The size and complexity of heat pump application is very wide, with appropriate specialist techniques for each application. For convenience, we examine applications by size.

#### 27.10.4.1 1–10 MW (thermal) schemes

Large-scale heat pump investments are attractive when the running time is long each year. Two types of application meet this requirement. These are base load space and water heating for district heating schemes[64,65] and heat-recovery techniques in large continuous industrial processes.[66,67] The compressors are usually of the high-speed centrifugal type or screw compressors.

Groundwater, sea-water, lakes or sewage treatment can provide the heat source for district heating schemes. Results from the Swedish Sala Municipal district heating network show that a screw compressor can provide 3.2 MW thermal energy at an annual COP of 2.7 (*Figure 27.18*). Availability in its first year was 80%. This heat pump operates throughout the year, providing the base load in winter and the hot water heating in summer.

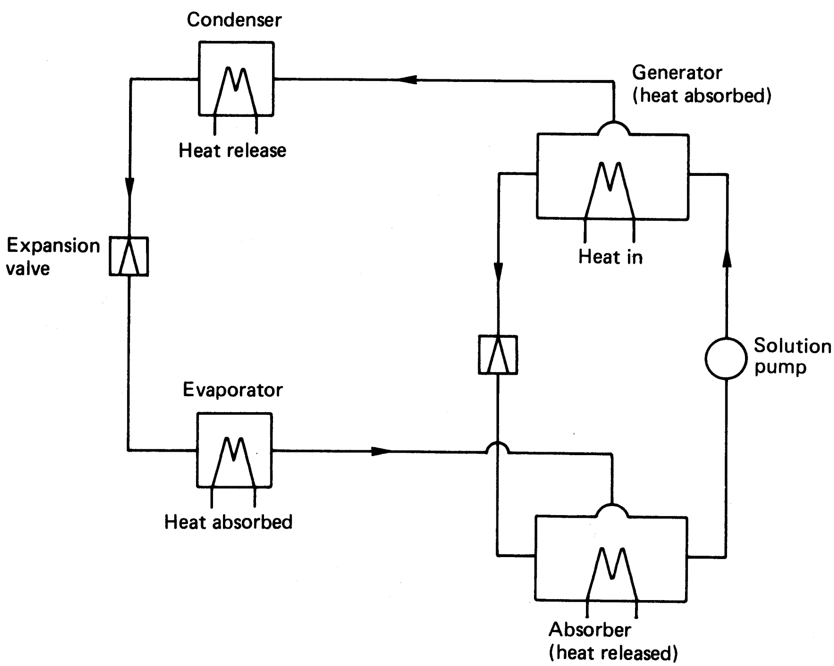


**Figure 27.14** Schematic diagram of an absorption heat pump

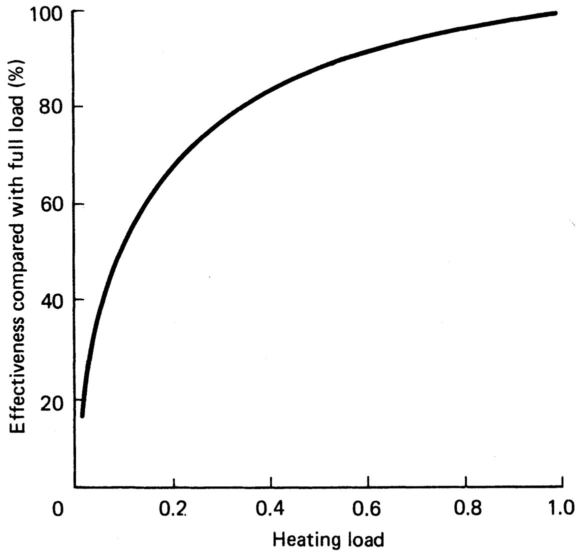


**Figure 27.15** The effectiveness of the part-load condition for an absorption heat pump (ammonia/water pair, 12 kW input). (Courtesy of McLinden[61])

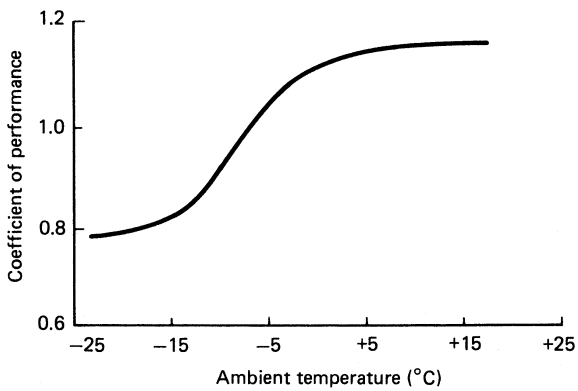


**Figure 27.16** The performance characteristics of an absorption heat pump (ammonia/water pair, 12 kW input, 70°C water supply temperature returning at 50°C)

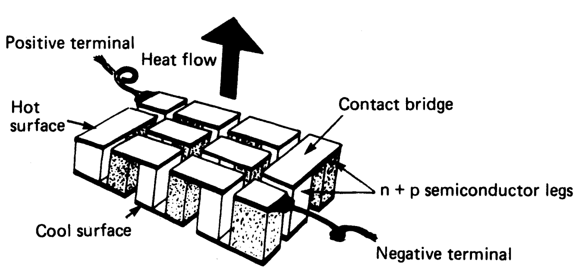


**Figure 27.17** The Peltier thermoelectric module (d.d. electric)

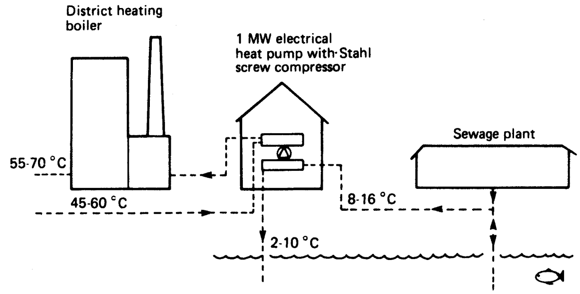


**Figure 27.18** Town sewage provides the heat for Sala, central Sweden, with an annual coefficient of performance of 2.7

Supplementary heating which is needed in the depth of winter is provided by a conventional oil-burning boiler.

Process heat treatment is illustrated by the 1 MW Milk Marketing Board dairy plant at Bamber Bridge, England. This dairy is a bottling and cartoning deport serving retail outlets. Two McQuay Templifier centrifugal compressors are employed in series (*Figure 27.19*). Recycled effluent from the bottle washers is stored and then pumped through both the evaporator and the condenser sections of the first heat pump. The outlet water from the evaporator at 7°C is directed into the dairy supply tank as chilled water for dairy services. The water leaving the condenser passes into the condenser of the second heat pump, where it is heated to 60°C and provides a boiler feed preheat and a crate washing unit. The overall coefficient of performance is 5.5.

*27.10.4.2 100 kW to 1 MW (thermal) schemes*

The three main applications are commercial buildings, small industrial batch drying plant and swimming pools.[68,69] The compressors are of the multicylinder piston or rotating vane types.

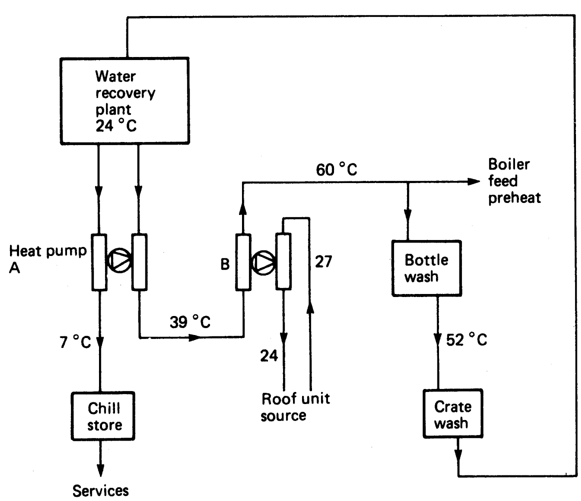


**Figure 27.19** Two McQuay centrifugal compressors operate up to 70°C to provide 1 MW of heat recovery in the British Milk Marketing Board's dairy at Bamber Bridge. The coefficient of performance under these conditions is 5.5

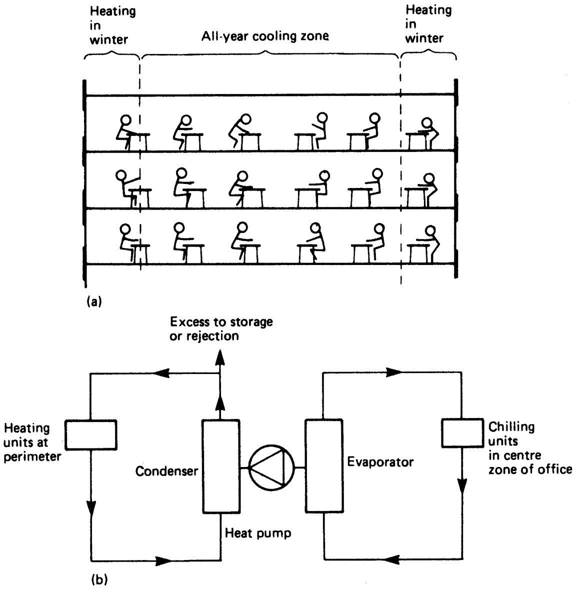


**Figure 27.20** Heat pump recovery in deep-plan offices: (a) section of a deep-plan office; (b) the cooling circuit provides the perimeter heating in winter

Deep open-plan offices require winter heating at the perimeter to combat the outdoor climate, but require permanent cooling of the central core. The heat pump enables the energy to be redistributed within the building (*Figure 27.20*). Such installations halved the energy cost of air-conditioned buildings in Britain, and formed the new concept of integrated environmental design. Coefficients of performances are 3–4.

The second batch of machines is usually a factory packages system for batch industrial drying.[70–72] Compact dehumidifiers which operate up to 80°C are now available for timber drying. Such machines are particularly suitable for the controlled drying required for hardwood to avoid timber splitting (*Figure 27.21*).

Swimming pools are particularly energy intensive. Internal design conditions must not exceed 70% relative humidity of the pool hall air if condensation and mould

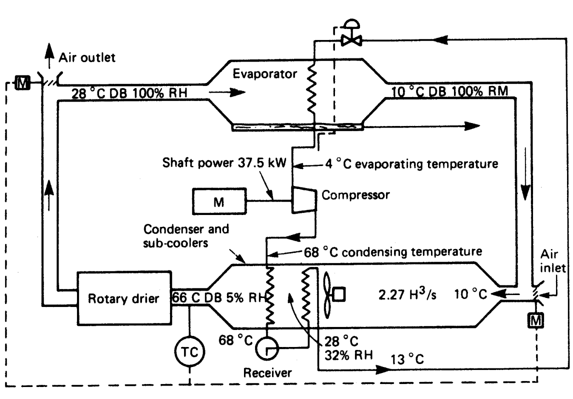


**Figure 27.21** A single-stage heat pump dryer with subcooler has a coefficient of performance of 4.4[71]

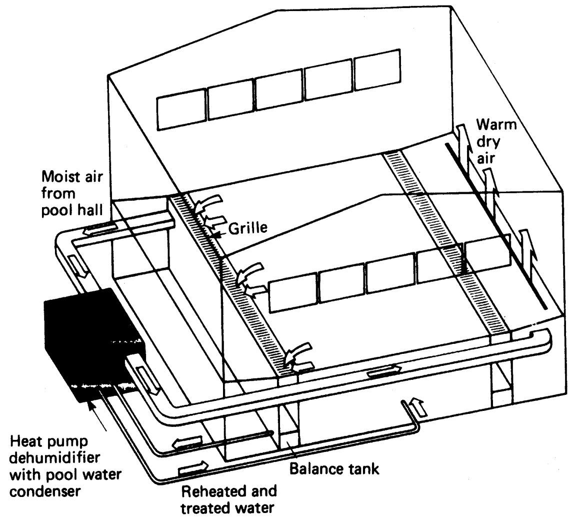


**Figure 27.22** Heat pump dehumidifiers can recover much of the sensible and latent heat from the warm moist air and return it to the pool water. Not only does this recover energy, but it also enables the conventional ventilation rate to be reduced[68]

growth are to be avoided. The conventional technique is to ventilate at a high rate and lower the moisture content of the air by dilution with air from outside. Heat pump dehumidification enables the moisture in the pool air to be controlled without losing great amounts of heat with high ventilation rates. The latent heat recovered from the moisture is used to heat up the pool water (*Figure 27.22*). The warm, moist air conditions mean that the heat pump can operate at a coefficient of performance of 5–6.

### *27.10.4.3 10–100 kW (thermal) packaged units*

Two types of machine of this size are factory packages. The most common is the reversible air-to-air space conditioner. It is reversible because, by an arrangement of valves, the unit can interchange evaporator and condenser by cooling in summer or heating in winter. The equipment is usually installed ‘through the wall’ in offices and shops, with each unit controlling a small zone within the buildings (*Figure 27.23*). It is also commonly sited on the flat roof of shops.

A modification of this principle is applied to large buildings, particularly older office blocks where the glazing area is large. In such buildings the individual heat pumps are attached to a ring main of recirculating tepid water. For those parts of the building needing cooling, the local heat pumps reject the heat to the ring main (*Figure 27.24*). Those parts of the building needing heating use the heat from the ring main as their heat source. Any net heating or cooling is provided from the central boiler or the central chiller.

The second and less common type is the air/water space heating heat pump.[73–75] They usually use outside air as the heat source and supply the heat to the house through conventional water radiators (*Figure 27.25*). They are often used in conjunction with supplementary heating because both the effectiveness and the output of such machines fall when the outdoor temperature falls and heating need is greatest (*Figure 27.26*). They also have a maximum water temperature of 55°C, which is lower than the figure for the conventional boiler of 80°C. Care must be taken, therefore,

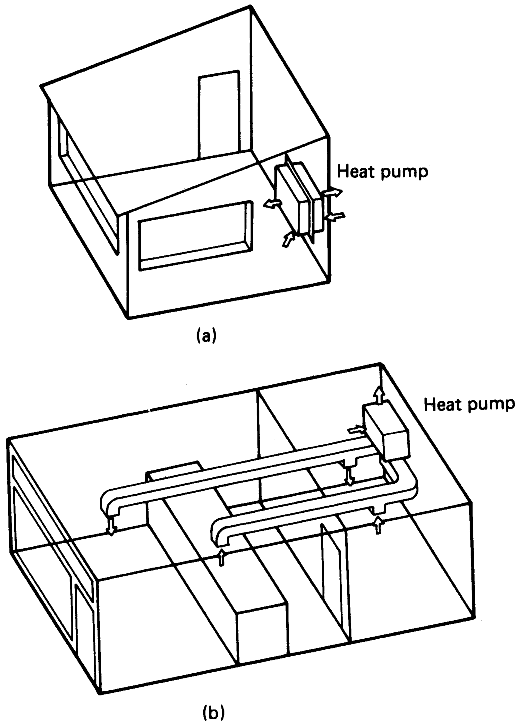


Figure 27.23 Reversible air-to-air room units can either heat or cool: (a) reversible air-to-air room unit; (b) self-contained ducted roof mounted heat pump

to ensure that the area of radiator is sufficient when operating at 55°C. There are two other cautionary points—noise and starting current surges. Air source heat pumps can be noisy and must, therefore, be selected and sited so that noise levels immediately outside the bedroom window are below 45 dB(A). Compressors with single-phase electrical drives greater than 1 kW rating must be checked with the local electricity company to see whether the electrical network would be unduly disturbed by the connection of such a pump. Soft-start units are now available on single-phase

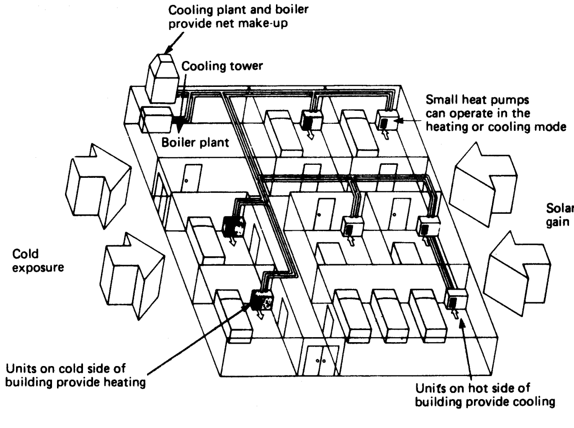


Figure 27.24 Linked room units can provide heating in some areas cooling in others

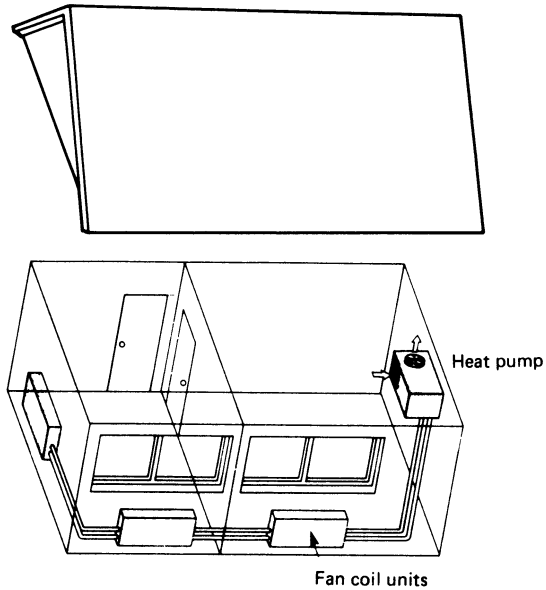


Figure 27.25 An air-to-water domestic heat pump. The heat pump is shown inside the roof space but it can be sited in the garden

domestic units. Such devices are particularly helpful if the heat pump is switching on and off frequently.

While ambient air is the usual energy source, groundwater can be used. Even the earth around the building can supply the energy, provided that a sufficient area of brine filled pipes is buried in it (*Figure 27.27*).

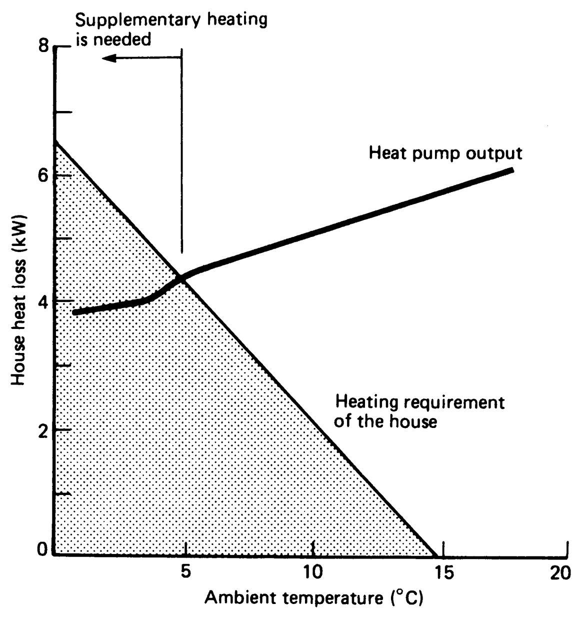


Figure 27.26 The output of an air source heat pump declines with colder conditions. The small step decline around 5°C is due to de-icing the evaporator

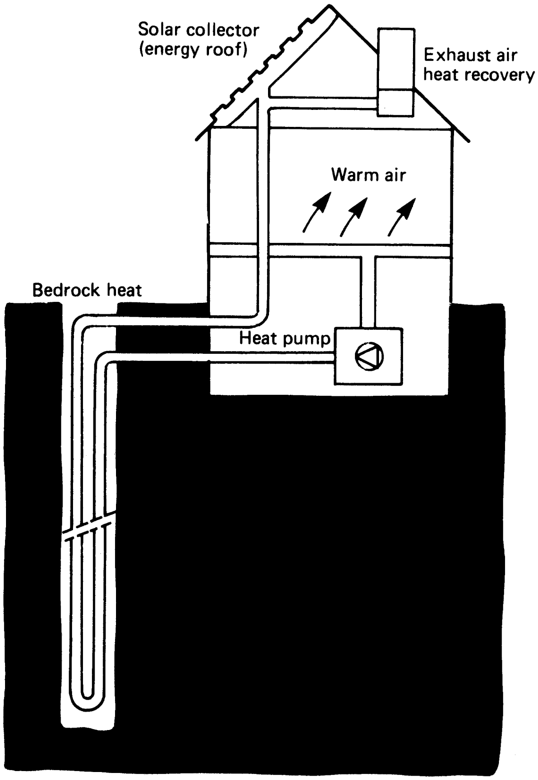


**Figure 27.27** Advanced house design uses the heat pump in conjunction with heat recovery. The 'chimney' is now a ventilator, the roof a solar collector and the floor a low-temperature heat emitter. The ground provides the extra energy[65]

*27.10.4.4 1–10 kW (thermal) packaged units*

Most recent technical advances have occurred in these packaged units. New types of compressor, notably the scroll orbiting (not rotating) compressor, reduce noise levels, are small in size and low in cost and are combined with improved ribbed heat-transfer surfaces and more efficient electric motors. The operating cycle of the scroll compressor is shown in *Figure 27.28* and shown in section in *Figure 27.29*.[76]

New variable-speed drive motors are available to minimise frequent on/off cycles with their consequent wear and intermittent performance. This means that proportional control becomes readily available. The compressor speed range can vary from 1800 rev/min (40% load) to 7200 rev/min (12% design load).[77]

There are three types of application. The first domestic use is a hot water heater. This is usually combined with a hot water cylinder (*Figure 27.30*). The heat source comes from inside the building. Such application is very attractive if interior cooling is needed simultaneously, e.g. cooling a beer cellar and using the reclaimed heat to provide hot water for washing the glasses. Conventional equipment has a maximum temperature of 55°C and, therefore, the volume of stored hot water has to be slightly larger than normal.[78]

The second domestic application is in a mechanical ventilation heat-recovery system. The cycle is illustrated in *Figure 27.31*[79] In a well-insulated house such units can provide 90% of the heating requirements. The heat pump can approach a coefficient of performance of 3.[79]

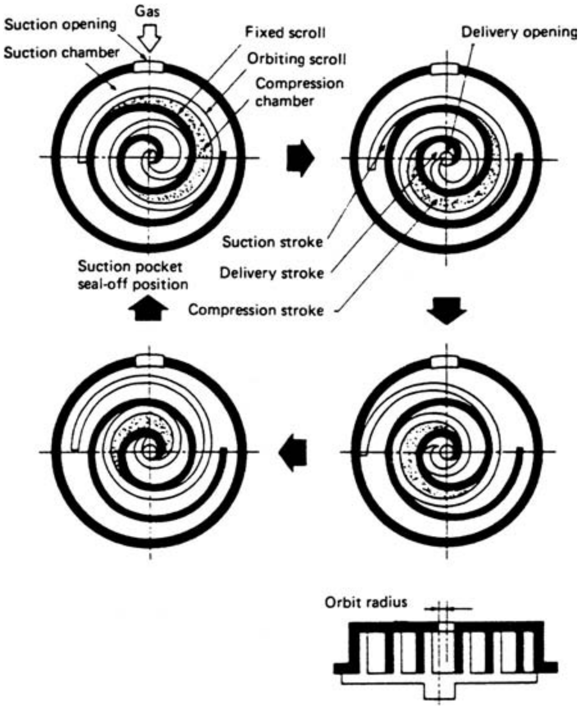


**Figure 27.28** The operating cycle of the scroll compressor

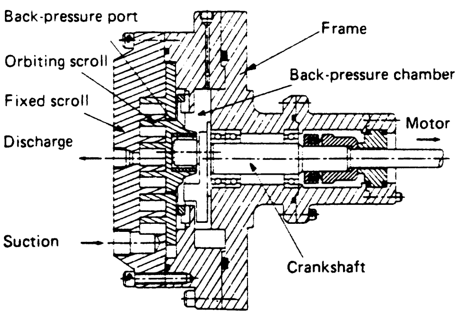


**Figure 27.29** Section of an orbiting scroll compressor

The industrial application is dehumidification. Portable units are available to dry out damp or newly built buildings. Fixed units are now being used to maintain low humidities in warehouses, particularly as warehouses are becoming automated and no longer require heating for the occupants.

*27.10.4.5 100 W to 1 kW (thermal) units*

Damp, cold conditions characterise the winter climate in the UK. Small heat pump dehumidifiers extract moisture and translate the latent heat into sensible heat. Cool, damp air enters the evaporator and is chilled, depositing much of its moisture. The same air is then reheated over the condenser and returned to the room. Present equipment has a coefficient of performance which varies from 1.1 to 2.0, the higher value being associated with warmer and damper conditions[80] (*Figure 27.32*).

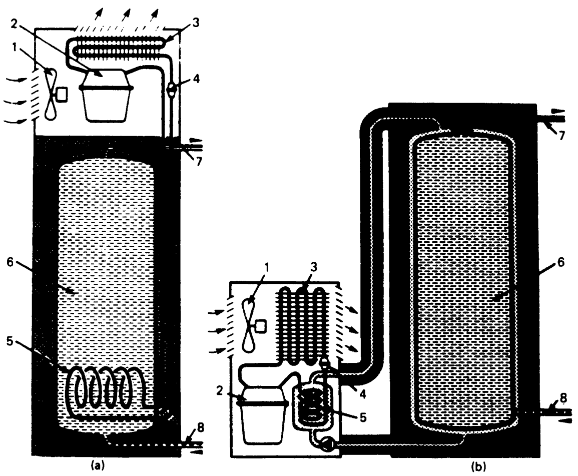


**Figure 27.30** A heat pump domestic water heater. Local water regulations may prohibit the direct immersion of a refrigerant heat exchanger into the water cylinder.[78] 1, Fan; 2, compressor; 3, evaporator; 4, expansion valve; 5, condenser; 6, storage; 7, hot water; 8, cold water

### *27.10.4.6 10–100 W (thermal) modules*

Peltier modules are effective ways of providing very small heat flows which can heat or cool. Their main application is to provide stable reference temperatures in scientific equipment.

## 27.10.5 Conclusions

Heat pump applications are very diverse. The expertise required varies widely with the different types of application. The very large plants (ca. 1 MW) are tailor-made for specific tasks which need much design analysis for successful

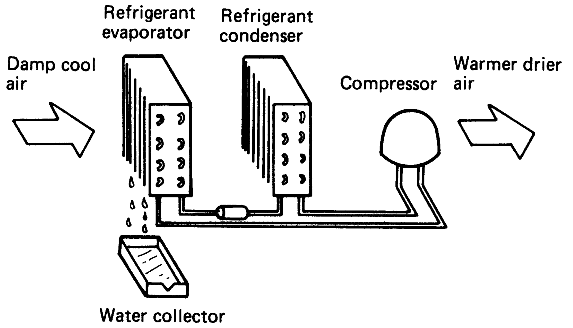


**Figure 27.32** A domestic dehumidifier removes water vapour and provides heat

integration. As the plant size decreases, the heat pump technology is built into packaged units and the application skills needed become those of a building service engineer. Illustrations of the performance and size of different applications are summarised in *Figure 27.33*.

In general, the heat pump is an advanced piece of engineering which saves energy by extracting it from a low temperature source and making it available at a higher and more useful temperature. The three key factors for its successful use are:

(1) where both heating and cooling are required, preferably simultaneously;
(2) where moisture must be removed, and preferably where some heating is needed simultaneously; and
(3) where the hours of use are long each year, so that the revenue savings can justify the increased initial cost which the heat pump incurs.

It also provides a dramatic reduction in carbon dioxide release and its associated greenhouse effect.

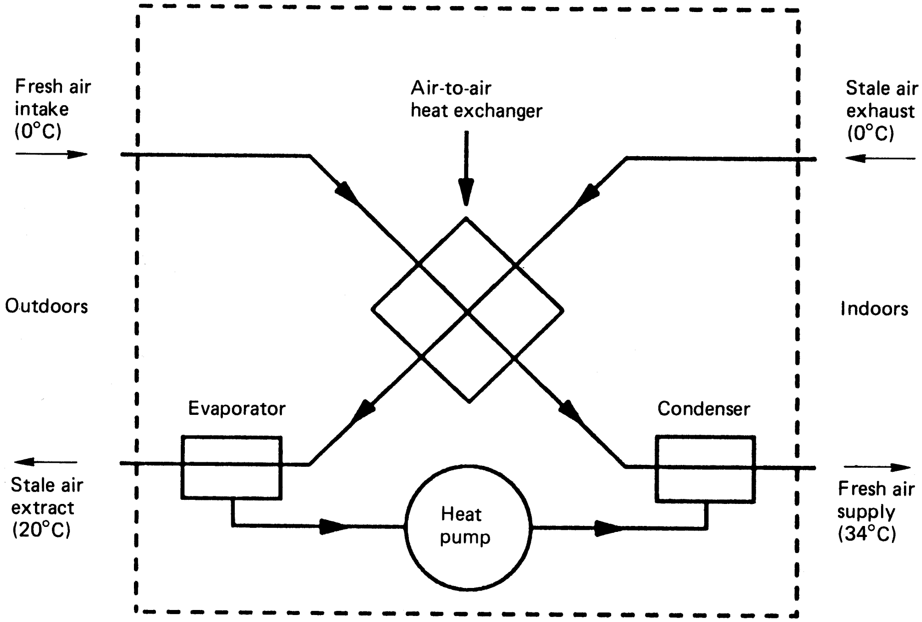


**Figure 27.31** Schematic diagram of a mechanical ventilation heat recovery pump

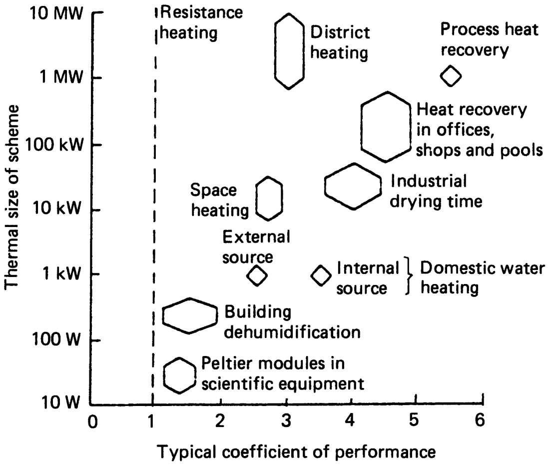


**Figure 27.33** Some coefficients of performance for heat pumps in different applications. Coefficient of performance = Heat out/Purchased energy

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