Energy and the environment

When discussing the physics of the atmosphere, we considered a few examples changes in the environment induced by human activity. One of the most important of these is the excess ‘global warming’ induced by increased carbon dioxide in the atmosphere. This in turn is related to the increased burning of fossil fuels which in turn is driven by demands for economic growth. In the past, growth in the economy has been tightly linked to an increased demand for energy. In this part of the course we shall (very briefly and only in outline) consider the following questions. How much energy do we need? How large are our energy reserves? Can we find cheaper, cleaner, energy sources?

How much energy do we need ?

To ask the question in this form presupposes a large number of political and social questions. In this section, I propose to consider how the demand for energy is analysed. For convenience, I shall leave the question of energy *conservation* until later, splitting off the question of ‘what is the most efficient method of doing what is wanted’ from the more basic question of ‘what is wanted’

The Figures show the growth of the rate of energy use analysed in terms of the various energy sources since about 1860. To date, most energy has been derived from fossil fuels; gas, oil and coal with a little wood and biowaste. With industrialisation, the rate of energy use has increased 30-fold. At first, the main fossil fuel was coal, since 1950 the major growth has been in the use of oil. In 1990, estimated world consumption of energy was 8730 million tonnes of oil equivalent (toe) or about 12TW. However, great disparities exist in the amounts of energy used per person in various parts of the world.

Energy use in tonnes of oil equivalent per person in different regions of the world (1990) [tonnes of oil equivalent; 1toe = 1.33kW)	
North America	7.82
Former USSR	5.01
Western Europe	3.22
Eastern Europe	2.91
Latin America	1.29
Middle East	1.17
Pacific	1.02
Africa	0.53
South Asia	0.39
World average	1.66

This table is still a crude average over many areas. The Figure displays data in terms of different countries and shows the variations more clearly.

Another way of analysing energy is in terms of end use. The figure shows the results of a study done in 1986 for the UK. Since then, the relative proportions of *primary* energy production between coal and gas have changed significantly. Coal usage has decreased by about 25% and gas increased by about the same. The total figure for *primary* energy has remained (roughly) constant. Countries vary, but the pattern of end-use is reasonably typical of an industrial nation. About 40% of the energy demand is for low-temperature heating and space cooling; about 20% for high-temperature heating (i.e. above the boiling point of water; mainly industrial) . About 30% is used in transport. Only about 5-10% is used for activities that require electricity (i.e. lighting, electrolysis, electronic equipment and so on. In developing countries a greater percentage of energy use goes in cooking and less in space heating but otherwise the distribution is similar. In both developing and developed countries, the average spend on energy per person is about 5% of annual income.

Energy resources (fossil and nuclear)

A rough inventory of the known exploitable resources is shown in the next figure (World Energy Council 1990). If current usage continues on the present trend, by the mid 21st century resources of oil and gas will be coming under pressure. This will encourage the use of (currently) marginal resources and further exploration (Rockall, Falklands) but these will be more expensive to exploit and prices will rise. Coal stocks will last at least a couple of centuries with current reserves. Total reserves (probably) give about 1000 years. There still remain local shortages. Japan is the obvious example. Europe (apart from U.K. and Norway) has no oil and only a little gas. This means that the industrialised world is becoming increasingly reliant on imports from the developing world, above all from the Middle East. Moreover, none of this addresses the environmental problems consequent on energy use.

The OECD has offered an analysis of how these problems occur. (*The OECD Compass project 1983*). One point is worth noting. Reference is frequently made to the *fuel cycle*. Most fuels are *NOT* part of a cycle (except for renewables and biofuels). You do not get bask to where you start from. Fossil fuels are irreversibly consumed and not replaced. With this proviso, the OECD 'fuel cycle' contains the following stages

- *exploration* (e.g. geological studies, prospecting, test drillings)
- *harvesting* (mining, drilling and – for biofuels real harvesting)
- *processing* (extraction of the fossil fuel and any purification process needed)
- *transport* (fuels are rarely close to the point of consumption)
- *storage* (where possible; note that electricity cannot be *stored* as electricity but must be converted into another form of energy for storage)
- *marketing* (look around you for examples of this!)
- *end use* (see the discussion earlier)

One must then consider the detailed implementation of these steps . We will consider a couple of examples later. The OECD considers the result of these activities under the term *residuals* – not only the waste released into the environment, but also the material removed from the environment and structural changes to the environment. These are given as

- *consumption* of resources needed to obtain the primary energy supply (e.g. equipment to build and maintain mines, energy to run the mine, land taken)
- *effluents* (these can be *material* such as solids, liquids, gases or *non-material* such as heat, noise)
- *physical transformations* (land filling, erecting buildings)
- *social/political* (changes in employment, populations)

In fact this mixes up different kinds of effects. Some of them are perhaps better described as impacts; it is obvious that there is no one way of tackling a list as varied as this.

An alternative is to use a *systems approach*. We draw a *system boundary* around the *components* of a system that undoubtedly interact with each other and call everything outside that the *system environment.* So far, we are merely making explicit a judgement that we are probably making implicitly anyway. Such a distinction is necessarily a matter for judgement and may vary depending on exactly what we are interested in. A simple example is a heating system where we might wish to draw the boundary round the heater and fuel and consider the atmosphere as the system environment. This enables us to define the question of what is the effect of the system on the local system environment; the *bubble of influence*. We will consider an example of atmospheric pollution in more detail later.

Fossil fuels

These are, and are likely to remain, the major source of energy for many years despite the increasing concerns about global warming. Thermal power stations (be they fossil or nuclear) have a heating element, a boiler and a turbine. From 1st year thermodynamics, the *Carnot efficiency,* η, of a heat engine is given by

$$\eta = (T_h - T_c)/T_h$$

where T_h is the temperature of the hot reservoir and T_c is the temperature of the cold reservoir. The cold reservoir is the environment (usually a river) and so, in practice, has a temperature of about 15^0C (288K). The hot reservoir can get up to 600-700^0C (900K or thereabouts). This gives Carnot efficiencies of the order of 70%. Real power stations are not reversible Carnot engines and cannot reach efficiencies of anything like this. A total efficiency of 42% would be reckoned to be good for a normal coal-fired power-station. This comes from the following.

- Suitably designed boilers can reach efficiencies of 90% in the transfer of heat to the working fluid
- A typical power station will have three steam turbines (high pressure-about 160bar, medium pressure- about 2bar and low pressure – about 0.035bar). The steam exiting the turbines is used to heat the water inlet to the boiler. The total efficiency of this setup is about 48%
- There are some (fairly small) mechanical losses and miscellaneous hot losses.

One device to improve the utilisation of the system is to construct a combined heat and power generator (CHP). The overall efficiency of this, η_{CHP} is defined as

$$\eta_{\mathrm{CHP}} = \frac{\text{net power output} + \text{heat recovered}}{\text{energy input}} \times 100$$

The gains are obvious (about 2/3 of the waste heat can be recovered). It works best for a fixed balance of heat and power (1:1 in many cases). In practical situations the ratio required may vary (For example, who needs domestic space heating in summer?). There is significant extra investment required in plant and heat pipelines (also there is a need for backup). If the CHP system is also a district heating scheme there may be problems of noise and pollution since the plant must be close to the district it serves.

Nuclear power

In principle, three methods of obtaining power from nuclear energy have been considered; *thermal reactors* (which obtain energy from the fission of isotopes of uranium or thorium), *breeder reactors* (which in addition to doing this also convert the natural uranium isotope U^{238} to a fissile isotope of plutonium, Pu^{239}) and *fusion reactors* (which use the reaction $^{2}D_{1} + {}^{3}T_{1} \rightarrow {}^{4}He_{2} + {}^{1}n_{o} +$ energy; the tritium being obtained from lithium by neutron bombardment). Only the first has been used to obtain power on a commercial scale. A few large-scale experimental breeder reactors have been built (PFR in Britain, Super-Phénix in France; both of these are now being decommissioned). A number of experimental fusion 'reactors' have been built. The most successful of these (the tokamak at Culham) have just about broken even (i.e. the fusion reactions inside the apparatus have delivered as much energy as that required to create the plasma needed to generate them). Commercial exploitation (if it is ever possible) is at least a generation away.

A large number of designs of nuclear reactor have been proposed (and indeed tried in the last half century). All of them have the same basic features.

- *The nuclear fuel.* In a fission reactor, the nuclei of uranium or thorium are broken up into two approximately equal parts by neutron bombardment. One typical reaction sequence is

  $${}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n} + 175\mathrm{MeV}$$

  The important points are (i) the large amount of energy released (ii) the fact that you get more neutrons back than are consumed (which gives rise to the possibility of a *chain reaction*) and (iii) the unavoidable production of radio-active isotopes. The neutrons produced by this reaction (*prompt neutrons*) are not the only ones produced. The immediate fission products also release neutrons through a beta-decay process on a timescale of seconds to minutes (*delayed neutrons*). An example of a reaction is

  $${}^{87}_{35}\mathrm{Br} \rightarrow {}^{87}_{36}\mathrm{Kr} + {}_{-1}e \rightarrow {}^{86}_{36}\mathrm{Kr} + {}^{1}_{0}\mathrm{n}\ )$$

  It is this fact that makes a nuclear reactor controllable. A chain reaction that relies on the prompt neutrons alone is a nuclear explosion. If maintaining the reaction relies on the existence of delayed neutrons, the process is controllable. The condition for establishing a chain reaction is a nuclear reactor is the *criticality factor*, *k*, defined as

  $$k = \frac{\text{neutrons produced in the nth generation}}{\text{neutrons produced in the (n - 1)th generation}}$$

  For control, *k* needs to be close to unity.

- Thus we require something to absorb enough of the neutrons to ensure that this is the case.
- *The moderator*. In a thermal reactor, this is done by slowing the neutrons down so that they are more likely to be absorbed by a nucleus (^{238}U or ^{235}U) rather than break it up. Neutrons are slowed down by allowing them to hit the atoms of a *moderator* (light nuclei that take away the initial kinetic energy of the neutrons). The neutrons are slowed to the velocities appropriate to the *thermal motion* of a gas. Two moderators have been used; graphite (in most reactors built in Britain) and water (in pressurised water reactors for example).
- *A method of getting the heat from the reactor core*. This is a (fairly) conventional piece of chemical engineering involving heat transfer circuits and boilers (see the diagram).
- There are two basic problems with this method of energy generation (i) the possibility of a major release of radioactivity; the Chernobyl explosion is the clearest example. (ii) the problem of disposal of the radioactive waste. Radioactive waste is conventionally divided into three types
- *low level* : which includes the waste produced by therapy in hospitals
- *medium level* ; an example would be the fabric, particularly the metals of a reactor
- *high level;* medium and long-lived decay products of the nuclear reaction; including actinides produced by neutron capture rather than nuclear fission

Most attention has been devoted to the last category; where the methods under consideration include incorporating the decay products in glass or artificial minerals and then burying them in deep repositories. However, the much larger volumes of low-level and medium-level waste are also a significant problem.

Renewable resources.

These amount, in the end, to harnessing solar energy directly or indirectly (with the exception of tidal power which in the end harnesses the rotational energy of the earth and geothermal which harnesses the internal heat of the earth). In principle there is a lot of solar energy; about 18000TW falls on the earth. The basic problem is collecting it; the energy density is very low. Current usage is as follows

1. Hydroelectric (6% of global energy requirements)
2. Biomass (i.e. wood-burning) 1.5% of global requirements
3. Tidal, solar, geothermal, wind *together* provide about 0.5% of global requirements

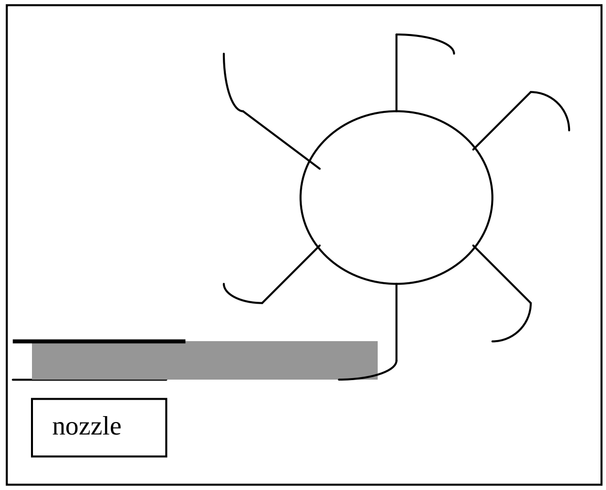
In other words, only hydroelectric is making a significant contribution. We will now consider each source in turn

Hydro-electric power

The main advantage of hydro-electric power is that the energy density is high. The largest schemes are >10GW capacity (Guri in Venezuela and Itaipu on the Brazil/Paraguay border). There is much untapped power particularly in the former Soviet Union. The drawbacks are serious; hydroelectric schemes require large dams. These cause large social and ecological changes

The basic method is simple. Water passes from a dam down a tube and through a turbine. The idea is to convert the potential energy of the water first into kinetic and then into electrical energy. If ρ is the density of water, Q is the flow-rate then P_0, the maximum power available to be generated is given by

$$P_0 = \rho g h Q \qquad (1)$$



where h is the height drop. Equivalently, one can look at the problem from the point of view of the kinetic energy; if the velocity of the water is u, the power available is $\rho Q u^2 / 2$ We shall briefly consider one kind of turbine; the *Pelton impulse turbine*. Consider the case where the water from the jet is hitting the bottom cup. If the velocity of the cup is u_t and the velocity of the jet is u_j, then if we take the ideal case where the cup deflects the stream by 180^0 and there is no friction to worry about then, with respect to the frame of reference of the cup, the speed of the water jet is $(u_j - u_t)$ both before and after the water hits the cup. (The direction of course is reversed). This is also the *change* of velocity seen in the laboratory frame. Thus the change of momentum of the fluid (and thus the force exerted on the cup) is

$$F = 2\rho Q(u_j - u_t) \qquad (2)$$

to the right in the diagram. The power transferred is

$$P = Fu_t = 2\rho Q(u_j - u_t)u_t \qquad (3)$$

This is a maximum for $u_j / u_t = 0.5$ in which case the power output is the kinetic energy of the water in the jet; i.e. the turbine is 100% efficient. Real efficiencies vary from 50% (for small units) to 90% for large commercial systems.

Small hydroelectric plants (less than 10MW) are being built across the world, particularly in China. Chinese figures give 4000MW current in 1990 plus 2000MW in development (not counting the Three Gorges project). Elsewhere, about 1000MW per year is being developed. A particular use is as spinning reserve for peak usage; an example of this is the Dinorwic plant in the U.K. The point is that hydroelectric plant can be started up very quickly.

Tidal power.

This is similar to hydro-electric power *except* that it is not a continuous source. In principle there is a lot of energy available but there is the problem both of energy density (how many estuaries are suitable) and of environmental problems. The largest tidal installation (and has been for many years) is at La Rance (France) with a capacity of 240MW. In principle the Severn estuary could generate 8000MW (6% of U.K. capacity). The configuration of the estuary is close to ideal but (i) tidal barrages are expensive (ii) it would drastically change the environment of the estuary.

The basic idea is to trap the tide behind a barrier and let the water out through a turbine at low tide. If the tidal range is R and the estuary area is A, then the mass of water trapped behind the barrier is ρAR and the centre of gravity is $R/2$ above the low tide level. The maximum energy per tide is therefore $(\rho AR)g(R/2)$. Averaged over a tidal period of τ, this gives a mean power available of

$$\overline{P} = \rho AR^2 g / 2\tau$$

This is too crude; it is necessary to further average the tides over a month (to allow for spring and neap tides). To get this power out requires special turbine (designed for a comparatively low head). Even so, it is not possible to get significant power out close to low tide. The total power output can be greatly increased by using the turbines as pumps close to high tide to increase the tidal head.

Wind power

This is not a new idea. In 1800 there were over 10000 windmills in Britain. Modern ‘wind turbines’ consist of a two or three bladed propeller (33m in diameter). The rate of power generated in a wind speed of Beaufort scale 6 (strong breeze; about 30mph) is 300kW. In the U.K. the average wind speed for usable sites is about 17mph and the output about 100kW. Hence the need for a wind farm.

An example is the Fair Isle scheme In 1982, a 50MW wind farm was built to generate electricity from winds averaging 818mph. This provides 90% of the usage of the island. The cost is about 4p/kW-hr (compared with the cost from fossil fuel for such a site of 13p-kW-hr). This shows that wind-power can be a preferred choice in some cases; it does not show that it is a major contender. The main problem is that the peak wind and the peak demand are unlikely to coincide. Further, large wind farms are unpopular. They are very visible and often on sites of considerable natural beauty.

Again, the basic physics is simple. The kinetic energy in a unit volume of air is given by $\rho u^2/2$ where ρ is the air density and u the wind velocity. The volume of air passing cross-section A perpendicular to the wind velocity in time t is given by uAt (or u per unit cross-section per unit time). If the angle of the wind direction to the normal of the cross section defined by the wind turbine is β, the volume of air passing through unit area of the turbine cross-section is $u \cos\beta$. Hence the maximum power per unit area

$$P_0 / A = (\rho u^3 \cos \beta)/ 2 \qquad (5)$$

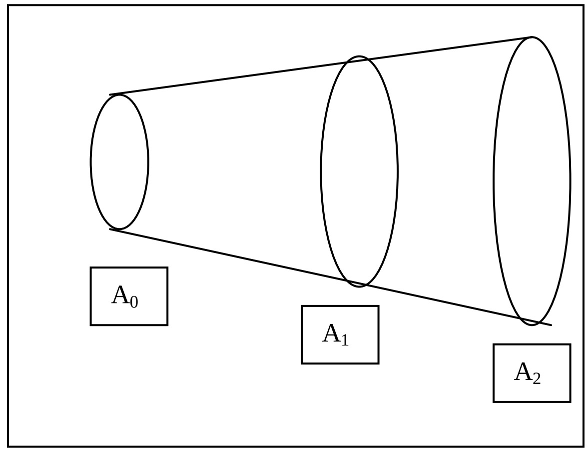
In principle, the maximum power available occurs when $\cos \beta = 1$ and then

$$P_0 /A = \rho u^3 / 2 \qquad (6)$$

In practice, only a small fraction of this is really available and the right-hand side of (6) is multiplied by a coefficient C_P , the *coefficient of performance*. The basic point of (6), that there is a power law dependence on the wind velocity remains. Effective wind turbines need high wind velocities.

It is possible to obtain a theoretical upper bound to C_P, the *Betz limit.* We consider airstreams at constant velocity passing through and by the turbine. The turbine rotor is considered as an *actuator disc*; there is a change of pressure across the turbine as energy is extracted and a decrease in the linear momentum of the wind.

Area A_1 is the area swept out by the rotor. Areas A_0 and A_2 enclose the stream of constant mass passing through A_1. The area A_0 is far enough upstream that it is not affected by the rotor. The area A_2 is at the position of minimum windspeed downstream (before the windfront reforms and the effect of the rotor is washed out). The force on the turbine is the reduction in momentum from the flow of air. If the rate of flow of mass is Q, then



$$F = Q\,(u_0 - u_2) \qquad (7)$$

If the air is moving with velocity u_1 as it passes the turbine, then the power extracted must be

$$P = Fu_1 = Q\,(u_0 - u_2)\,u_1 \qquad (8)$$

and the loss of energy per unit time is the power extracted from the wind i.e.

$$P = Q\,(u_0^2 - u_2^2)/2 \qquad (9)$$

For a 100% efficient turbine, these can be equated , which gives

$$u_1 = (u_0 + u_2)/2 \qquad (10)$$

Thus the air speed through the rotor must be at least half the unperturbed wind speed. The mass of air flowing through the disk per unit time is obviously $Q = \rho A_1 u_1$, so the power must be

$$P = \rho A_1 u_1^2\,(u_0 - u_2) \qquad (11)$$

If we now substitute for u_2 using equation (10) we have

$$P = 2\rho A_1 u_1^2\,(u_0 - u_1) \qquad (12)$$

The *interference factor a* is the fractional decrease in the wind speed at the turbine. Thus,

$$a = (u_0 - u_1)/u_0 = (u_0 - u_2)/2u_0 \qquad (13)$$

We can now use this to substitute for u_1 in equation (12), and obtain

$$P = (\rho A_1 u_0^3/2)\,[\,4a\,(1 - a)^2\,] \qquad (14)$$

If we compare this with equation (6), it is clear that the coefficient of performance, C_P, is given by

$$C_P = 4a\,(1 - a)^2 \qquad (15)$$

The maximum value of C_P occurs for $a = 1/3$, when $C_P = 0.59$. In practice, a modern wind turbine can manage a C_P value of about 0.4. Given this factor, the generation of energy is about 95% efficient (ie the efficiency of the turbine generator itself). Wind systems are of most use in niche areas where connecting to the grid is expensive. Since wind energy is variable they need a backup (ie a battery or the grid itself). Of all renewables, wind is the closest to being competitive with conventional fossil fuels. Most commercial projects are based on *wind farms*. The individual generators must be separated by about ten times the blade length and a further buffer zone round the farm is required. It has been estimated that wind energy could contribute 10% of U.K. energy requirements. This would need 40,000 330kW generators. That is a large wind farm

Wave power

In principle, large amounts of energy can be obtained from waves. Most devices are designed to extract energy from deep water waves, where the mean depth of the seabed, D, is greater than half the wavelength of the wave, λ. The basic properties of such waves are

- the surface waves are sine waves of irregular phase and direction
- the motion of any particle of water is circular; the waves move but the water does not
- water on the surface stays on the surface
- the amplitude of the motions of the water particles decreases exponentially with depth
- the amplitude of the surface wave is independent of the wavelength or velocity
- a wave breaks when the slope of the surface is about 1 in 7.

The power in a wave comes from the change in potential energy of the water as it rotates on the circular paths beneath the surface. It can be shown that the power carried forward by a wave is given by

$$P = \rho g^2 A^2 T / 8\pi \qquad (4)$$

where A is the amplitude of the wave at the surface and T is the period of the wave. Two devices intended to extract this power are the *Salter duck* and the *oscillating column*. The Salter duck consists of a cone that oscillates with the waves and is connected to a rotary pump that drives a generator. The oscillating column uses the wave to drive a trapped air column past a turbine. A number of prototypes have been tried (on about 1/10 scale in the U.K. in the early 1980's) but the economics of the power generation is not yet good enough for a full commercial trial.

Biomass (*as fuel*)

Second in importance to hydro (at present) is the use of biomass as a renewable fuel. The term covers domestic, industrial and agricultural dry waste material, wet waste material and crops. The U.K. generates 30 million tonnes of solid waste per year (0.5 tonne each). If all that could be incinerated was incinerated, this would generate 1.7GW (5% of U.K. requirements). The essential difference between this and fossil fuels is that the biomass cycle is a true cycle provided that for each plant used as fuel a replacement is planted. Examples of biofuels include

- *Gaseous biofuels* are used for (a) heating and cooking, and (b) in engines for electricity and heat generation, and occasionally for transport. Examples include *biogas* (CH_4 and CO_2) from anaerobic digestion of plant and animal wastes, and *Producer gas* (CO and H_2) from gasification of plants, wood and wastes.

- *Liquid biofuels* are used mainly for transport fuels. Examples are: oils from crop seeds (e.g. rape, sunflower), esters produced from such oil, ethanol from fermentation and distillation, and methanol from acidification and distillation of woody crops.

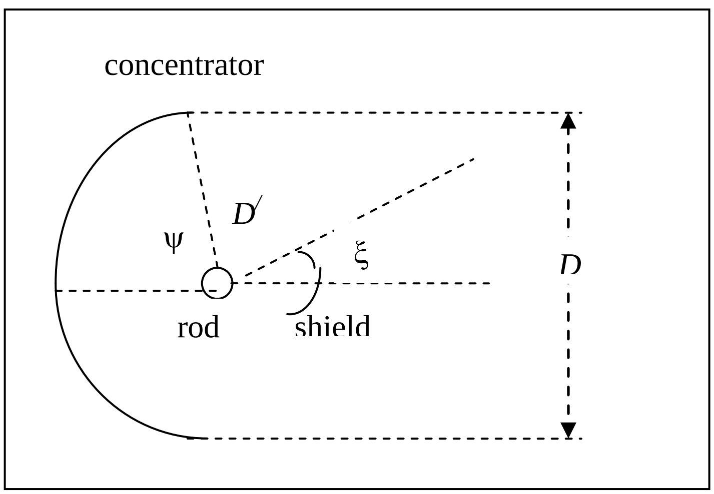
- *Solid biofuels* : Examples are: wood from plantations, forest cuttings, timber yards and other wastes, charcoal from pyrolysis, and refuse derived fuels, e.g. compressed pellets.

A major user of biomass is Brazil; the source being waste from the sugar-cane industry. Bagasse (residue after crushing the cane) and barbojo (leaves of the cane). Perhaps 67% of the 80 sugar-cane producing countries can use this as fuel.

Solar power

The simplest way of making use of energy from the sun is to turn it into heat. A black surface directly facing full sunlight can absorb 1kW / m^2. This is already used in Australia, Israel, Japan, Southern USA. The last has 350MW plants based on this idea.

Solar energy can be either *direct* or *diffuse*. Only direct radiation can be concentrated. The energy received from the sun at a given place depends on the latitude, time of day and season. If you wish to maximise the solar energy absorbed on a surface, you must slant it so that its normal points at the sun. For best results, the orientation should change during the day, and even correcting the angle from day to day to allow for the declination with the seasons. It is usually not worth the cost to do this. It is enough to set the surface to face the sun at noon and fix the angle with the horizontal to this. In the U.K. the relevant angle is 30^0 from the horizontal for solar panels. For some applications a *concentrator* can be used. In principle, a paraboloid is the the most efficient, but a parabolic trough is much easier to build. Referring to the diagram on the right, the power absorbed by the central rod (per unit length) is $P_{abs} = \rho_c \alpha D I$ where α is the absorbance of the rod and ρ_c is the reflectance of the trough.



Since D is the width of the trough, the area of sunlight entering the trough per unit length is also D. The irradiance from the sun is I. The rod will lose energy by radiation. Radiation that goes towards the trough is lost since it goes back out the concentrator into the environment.The shield will reflect the radiation back onto the rod over an angle 2ξ. So the angle over which radiation is lost is $2(\pi - \xi)$. So the radiation lost is

$$P_{rad} = \varepsilon\sigma T_r^4 (2\pi r)(1 - \xi / \pi)$$

where ε is the emissivity of the rod, *r* is its radius and T_r is its temperature. The best you can do is to arrange the abosrber so that it covers the rod unless it is directly receiving radiation from the collector, in that case $\xi + \psi = \pi$, when the power loss is $P_{rad} = 2\varepsilon\sigma T_r^4 (r\psi)$.The rod must be at least as wide as the solar image, i.e. $r = D'\vartheta_s$ where ϑ_s is the angle subtended by the solar image, about 4.6×10^{-3} radians. The maximum temperature is for the energy balance of the rod ie $P_{abs} = P_{rad}$.. Putting in typical values, gives a value of about 1150K. In practice, temperatures of 950K are obtainable. This is high enough for efficient electricity generation. Also, it is the basis of the solar furnace. Another approach is the *solar tower*, using sun-tracking mirrors to focus the energy onto a central point.

Solar collectors. The solar radiation is absorbed and the absorber is heated up to about 80^0C. The absorber should be painted black (absorption coefficient nearly unity). The heat is then transferred to water tubes. the system can then be run in a similar way to a standard boiler. A certain amount of heat is lost in conduction to the supports, convection and radiation. Radiation loss is the most significant. Recall the Stefan-Boltzmann law, $E = \sigma T^4$. If the temperature is 80^0C (353K), then the radiated energy is 880W/m^2. This is a substantial fraction of the total available; S = 1353W/m^2. The main problem is therefore to overcome the radiation losses. ‘Black chrome’ is used as the absorber. This has a high absorption coefficient for the wavelengths of solar (incoming) radiation, but a low absorption coefficient for the outgoing terrestrial radiation. Also, glazing is placed above the collector to reduce convection. Modern solar collectors have an area of 3m^2. The covering glass plate has a transmission coefficient of 90%

Let us consider this in more detail. In the arrangement described above, of the incoming radiation flux, *SA* (where *A* is the area of the plate), a fraction *t* is transmitted through the glass covering and a further fraction, *a* is absorbed. Ignoring losses from convection, radiation and conduction, the net power absorbed , *P,* is therefore *SAta.* If we assume that this is all transferred to the fluid in the heat exchanged, then the heat gained per unit time by the water flowing through the heat collector is

$$P = C\frac{dm}{dt}(T_{out} - T_{in}) = C\rho Q(T_{out} - T_{in}) \qquad (16)$$

where d*m* /d*t* is the mass rate of flow of the water, T_{out} is the temperature at the outlet of the collector and T_{in} is the temperature at the inlet. In the second identity ρ is the density and *Q* the flow rate. This is, of course, an idealisation; there are bound to be some losses. These can be expressed as an effective *thermal resistance* of the collector. We define this resistance *R* therefore as

$$\text{Energy losses} = (T_{out} - T_{in}) / R \qquad (17)$$

The *capture efficiency*, n, of the system is defined as the fraction of solar power impinging on the device that is converted into useful heat. The heat in the pipes is thus given by

$$taSA - (T_{out} - T_{in}) / R = nSA \qquad (18)$$

and so we have

$$n = t\,a - (T_{out} - T_{in})/(RAS) \qquad (19)$$

It is common to define U, the *energy transfer coefficient* as 1 / RA which gives finally

$$n = t\,a - U\,[\,(T_p - T_a) / S] \qquad 20)$$

This is *the Hottel-Whillier-Bliss equation*. The parameters (ta) and U are usually used to characterise a particular solar water heater.

Consider an example where we put in a bit more detail. A set of numbers are given in the table below:

Solar Constant	S	700Wm^{-2}
Temperature of the collector (set equal to the output temperature of the water)	T_{out}	35^{0}C
Temperature of the cover	T_c	35^{0}C
Temperature of the surrounding air	T_{air}	5^{0}C
Temperature of the sky	T_{sky}	-10^{0}C
Transmission coefficient and absorption coefficient of the collector	ta	0.9
Emissivity of glass	ε	0.1
Specific heat of water	C	4184Jkg^{-1}K^{-1}
Convection coefficient of the system (i.e. the heat lost by convection between the collector and the glazing plate)	h	2.82Wm^{-2}K^{-1}
Area of collector	A	3m^2
Rate of flow of water through the collector	dm/dt	0.042kg sec^{-1}
Input temperature of the water	T_{in}	30^{0}C

The losses due to absorption and transmission through the plate are 133Wm^{-2}. If the over is at the outlet temperature of the water, then the net radiation losses are given by $\varepsilon\sigma\left(T_c^4 - T_{\text{sky}}^4\right) = 23.9\ \text{Wm}^{-2}$ and the convection losses are $h\left(T_c - T_{\text{air}}\right) = 84\ \text{Wm}^{-2}$. This leaves 459Wm^{-2} to heat the water. If there are 2% losses in the heat exchanges (which is good), this costs another 9.2Wm^{-2} leaving about 450Wm^{-2}. If the water is heated by 5^{0}C, this means that the two parameters characterising the heater are ta = 0.81 (which is good) and U = (23.9+84+9.2)/5 = 23.4Wm^{-2}K^{-1} – which is bad because we have not double-glazed the cover. A decent value would be in the range 6-8Wm^{-2}K^{-1}. This system could heat about 232 litres of water per hour by 5^{0}C.

Solar photovoltaics
Solar radiation can be converted directly into electricity by solar photovoltaic cells. (Examples of use include watches/calculators, solar arrays for space craft). Practical cells made of amorphous silicon. Efficiencies are 10-20%. Hence a panel of cells 1m^2 facing full sunlight will give 100-200W. i.e. large area required for significant amounts of power. In 1990, world capacity was about 50MW. To meet WEC (World Energy Council) projections we would need 1000 times this amount by 2020. Only a few 'trials' of large-scale power production; e.g. Sri Lanka; 1.3kW solar array backed by 2200A-hr battery to provide lighting and refrigeration for vaccines in a hospital

Energy conservation
The other obvious approach is to reduce the energy demand. Energy conservation is often specific to the process and is difficult to treat in a general fashion. Since a large part of the energy demand in most countries is for space heating, it makes sense to consider this as our basic example of conservation. In this case, we must consider a number of issues. There is the basic physics of heat transfer and thermal insulation. There is the tradeoffs that are essential between an energy-efficient building and other conditions that must be considered. Here we consider the example of ventilation. Finally, we consider the energy breakdown of an average house.

Heat transfer and thermal insulation
Heat can be transferred by conduction, convection and radiation. Thermal insulation reduces the transfer of heat from one point to another, especially from the interior of a building to the outside. Effective insulation reduces the amount of heat that has to be supplied (i.e. reducing energy bills).

The effectiveness of an insulator is measured by its thermal conductivity κ. This is defined from the Fourier heat equation. Fourier asserted that heat flow per unit cross-sectional area, *J*, is proportional to the temperature gradient i.e.

$$J = -\kappa \frac{\partial T}{\partial x} \qquad (21)$$

The negative sign states that heat flows down the temperature gradient; from hot to cold. Typical values of κ (Wm^{-1}K^{-1}) are Al (160), steel (50), brick (0.84). Air is a good insulator but should not be in motion or convection will transfer heat.

Heat transfer by convection is usually divided into *natural convection* (where the fluid moves without any forcing) and *forced convection* (where the fluid is moved by draughts). Natural convection is described by Newton's law of cooling.

$$J = k(T - T_0)$$

where T is the temperature of the object and T_0 is the ambient temperature. *k* is the convection coefficient measured in Wm^{-2}K^{-1}.

Heat loss by radiation is given by the Stefan-Boltzmann law $J = \sigma T^4$. We have discussed this in some detail in previous sections.

Since in all cases, we are interested in the problem of heat transfer through the parts of building, it is convenient to choose a measure that does not depend on the mechanism. Engineers use a measurement to quantify the thermal behaviour of a structural element. The *U-value* (or thermal transmittance coefficient) is the rate at which heat flows through an area of $1m^2$ of an element when the temperature change across it is 1^0C. Clearly, this is most easily related to the thermal conductivity. We can express the heat transfer equation as a finite difference equation,

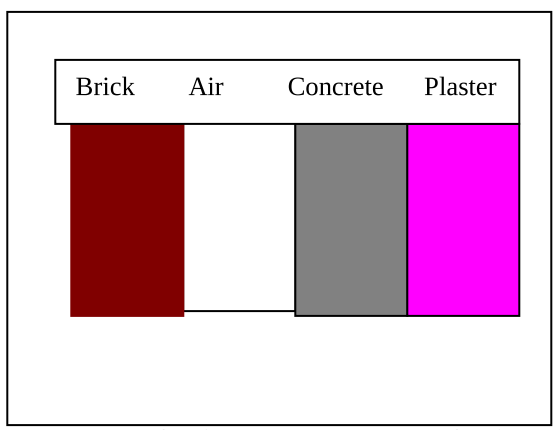
$$J = -\kappa \frac{\Delta T}{\Delta x}, \qquad (22)$$

Thus from the definition of U given above, $U = \frac{J}{\Delta T} = -\frac{\kappa}{\Delta x}$.

Radiation losses are forced into this form. For convection (as treated above) $U = k$ The total *U-value* for a complex system is obtained by using Kirchoff's law to sum the resistances. We define the *thermal resistance* $R = \kappa^{-1}\Delta x$. There are also resistances due to the presence of interfaces. These are given by *heat transfer coefficients h.* Thus the total U-value for a complex wall with heat transfer coefficients h_{in} and h_{out} for transfer into and out of the wall respectively is given by

$$1/U = 1/h_{in} + \sum_j R_j + 1/h_{out} \qquad (23)$$

For example, a single window has $U = 5.7 Wm^2K^{-1}$. Since a double-glazed window has a 2cm air space, U is (roughly) halved; the *lower* the value of U, the better the insulation. Consider a cavity wall as an example. Let us assume that the thermal conductivities are as follows ($Wm^{-1}K^{-1}$) brick (0.8), concrete (0.2), plaster (0.17) and that all the materials are 0.1m thick. The thermal *resistances* (m^2KW^{-1}) are plaster/air interface (0.12), brick/air interface (0.16), cavity (including interfaces) (0.19). The thermal resistances of the materials are



brick = 0.1/0.8 = 0.125
concrete = 0.1/0.2 = 0.5
plaster = 0.1/0.17 = 0.59.

Hence the U value is given by
U = 1/(0.125+0.5+0.59+0.19+0.06+0.12) =0.63
ignoring the two interfacial transfer coefficients. Typical values for these would be $h_{in} = 7\ Wm^{-2}K^{-1}$ and $h_{out} = 18\ Wm^{-2}K^{-1}$. This gives a final *U-value* of $0.56 Wm^{-2}K^{-1}$

Heat loss in buildings

The amount of energy lost from a particular building depends on the following loss factors;

- Insulation of the building
- Area of external surfaces of the building
- Temperature difference between internal and external environments
- Air change rate for ventilation and
- Degree of exposure to climatic effects, such as wind.

Each of these can be considered in terms of U values. It is convenient to divide these into two main kinds. *fabric loss and ventilation loss.* Fabric loss is the heat loss through the external 'skin' of the buildings (walls, floor, ceiling, windows) and can be written as

$$P = UA\,(T_{in} - T_{air}) \tag{23}$$

where P is the power loss, U is the effective U-value for the building and $(T_{in} - T_{air})$ is the temperature drop across the 'skin' of the building. The largest U values are usually for the windows, but the largest losses are usually through the walls; the effect of the much greater area dominates the effect of the U value. *Ventilation losses* are the other major contribution to heat losses. Ventilation is also an essential part of building design. (Most people need to breathe). The average person (mass 84kg) requires oxygen at a rate of 50ml/kg[bw]/min where kg[bw] is the body weight of the person in kg i.e. for the average person, 4200ml/min. Obviously the exact amount depends on what you are doing; 2000-3000ml/min (at rest) to 6000ml/min (athlete running). Heat is lost through ventilation (energy taken away by the convecting air). This is given by

$$Q = mC_P\,\Delta\theta \tag{24}$$

where m is the mass of air, C_P is the specific heat at constant pressure and $\Delta\theta$ is the temperature difference between the inside and outside of the building. Consider a room of volume V. If it takes t seconds to replace all the air in the room, then the rate of heat loss is $V\rho C_P\Delta\theta/t$ (where ρ is the density of air). If n is the number of times the volume of air in the room is expelled in one hour, the total volume of air moved is nV and so the rate of heat loss is

$$J = nV\rho C_P\Delta\theta/3600.$$

This is a sizeable energy loss, but is unavoidable.

Buildings also have a number of sources of heat (apart from the explicit heating system). These include

- solar heat through windows, walls and roof
- body heat from inhabitants
- heat from lighting equipment and electrical appliances (TV, fridges and so on)
- heat from cooking processes
- water heating

Added together, these can be far from trivial and should be taken into account when designing the heating system required.

Summary heat balance in an average house.

Divided into energy sources, the basic energy usage (per year) for an average house in the UK is

Electricity (MJ)	20232
Gas (MJ)	85460
Petrol (MJ)	87750
Food (MJ)	23029

The electrical budget can be split up as follows (note the efficiency savings as shown in the last column)

Appliance	1990 model (kW-hr)	current model (kW-hr)	energy efficient model (kW-hr)
Cooker	840	780	370
Washing machine	210	180	70
Dishwasher	500	430	300
Refrigerator	350	300	60
Fridge-freezer	730	500	275
TV	200	140	100
Lighting	370	370	105
TOTAL	3200	2700	1280