# Chapter 3

## POSSIBLE PREVENTIVE MEASURES

*What actions can the world community take to limit the increase in the amount of carbon dioxide in the atmosphere?*

3.1 In chapter 2 we explored the possible consequences of the enhancement in the greenhouse effect brought about by the increased concentration of greenhouse gases in the atmosphere. We reached the conclusion that governments should take action to prevent the concentration of carbon dioxide rising to the levels that will be reached if emissions from burning fossil fuels continue to increase, or even continue for the next 100 years at their present rate. In this chapter we identify and discuss different types of measure that could be taken to achieve that result.

3.2 Although the main focus for debate has been reducing the amounts of carbon dioxide emitted as a result of burning fossil fuels, there has also been considerable interest in other approaches that could in theory be used. We look first at three approaches which seek to solve the problem by managing other aspects of the global carbon cycle, and involve respectively:

preventing the carbon dioxide produced when fossil fuels are burnt from reaching the atmosphere (3.4-3.14)

increasing the amounts of carbon dioxide removed from the atmosphere by growing vegetation (3.15-3.23)

increasing the rate at which carbon dioxide is taken up by the surface layer of the oceans and transferred to the deep ocean (3.24-3.26).

3.3 We then look at the scope for responding to the problem by changing the ways in which the world obtains and uses energy. Changes that would reduce carbon dioxide emissions can be categorised under three headings:

reductions in the use of energy (3.28-3.34)

greater efficiency in the use of fossil fuels (3.35-3.43)

substitution of other energy sources for fossil fuels (3.44-3.52).

The challenge is so huge that an effective response to the threat of climate change will certainly require different types of measure to be used simultaneously and on a very large scale.

### MANAGING ASPECTS OF THE CARBON CYCLE

#### *PREVENTING CARBON DIOXIDE FROM REACHING THE ATMOSPHERE*

3.4 The traditional 'end-of-pipe' solution to a pollution problem is to fit equipment to a chimney or outlet and remove the polluting substance at that point so that it can be disposed of in some other way.[1] It is technically possible to do this with the carbon dioxide produced when fossil fuels are burnt. It would then have to be disposed of as a waste under conditions which ensure that it will not reach the atmosphere. Possible additional uses for carbon dioxide in the chemical and food industries are on a small scale relative to the quantities that are being produced, and in any case would not prevent it from entering the atmosphere eventually.

3.5 The carbon dioxide recovered could be disposed of by injecting it into deep geological strata, which naturally contain enormous quantities of carbon (figure 2-III). The most suitable geological settings are depleted oil and gas fields, deep underground formations containing saline water, or coal formations which are too deep to mine.[2] The pore spaces in such strata are large enough to contain a significant fraction of the carbon dioxide produced globally by burning fossil fuels for many decades to come. The oil industry has practical experience of injecting carbon dioxide in two contexts: as a technique to extract a higher proportion of the oil in a field and, more recently, to dispose of carbon dioxide after its removal as a natural constituent of gas from certain fields (appendix D, box D).

3.6 Technologies for recovering carbon dioxide are well developed, and could be incorporated in new combustion plants or retro-fitted to existing plants. Two approaches are available:

> capturing carbon dioxide from the mixture of flue gases leaving the plant, by applying technologies developed to remove it from natural gas (appendix D, D.15-D.18);
>
> operating the combustion process with oxygen rather than air so as to produce a flue gas which is up to 95% carbon dioxide. Some of the carbon dioxide has to be recycled in order to moderate the boiler temperature.[3]

Calculations have shown that the second approach may be among the least energy-intensive processes for recovering carbon dioxide.[4]

3.7 The loss of efficiency in generating electricity has to be taken into account alongside the costs of installation and operation. Using the first approach is estimated to increase the cost of generating electricity by between 51% and 66% for gas-fired plant and between 20% and 86% for coal-fired plant; and to give costs for emissions avoided of £34-35/tonne carbon and £18-70/tonne carbon, respectively. The second approach (in which the cost of capturing carbon dioxide is replaced by the cost of separating oxygen from air) is estimated to increase the cost of electricity generation by 85% for gas-fired plant and 27% for coal-fired plant; and to give costs for emissions avoided of £13-57/tonne carbon.[5]

3.8 These technologies are suitable only for very large installations. To achieve a comparable result for dispersed energy uses in transport or the home, it would be necessary to decarbonise fossil fuels at a central point and distribute energy in the form of hydrogen. That would involve large energy losses. The possibility of using hydrogen as an energy carrier is discussed later in this report (8.61).

3.9 The carbon dioxide recovered would be transported to the disposal site by pipeline in liquid or supercritical[6] form. The estimates quoted above do not include the cost of that, or of injection, but these would be small by comparison: £1.6-2.3/tonne carbon/100 km for transport by pipeline, and £0.8/tonne carbon or £1.4/tonne carbon for injection into, respectively, saline aquifers and depleted gas fields.[7] Further information about disposal into deep underground strata is in appendix D (D.19-D.25).

3.10 On the assumption that the carbon dioxide would be in supercritical form, provisional estimates are that the total capacity of suitable geological strata in Europe is about 200 gigatonnes of carbon (GtC), equivalent at the present rate to 770 years of emissions from European power stations. Of that capacity, 89% is in the form of saline aquifers in the territorial waters of the UK and Norway. In some aquifers horizontal movement of the injected carbon dioxide would be prevented by natural seals. Simulations over 1,000 years suggest that in other aquifers the carbon dioxide would migrate less than 4 km before dissolving completely in the groundwater, with some becoming permanently fixed through reactions with host minerals;[8] monitoring of injection already taking place taking place under the North Sea supports that conclusion.[9]

3.11 The engineering of a system for carbon dioxide disposal would have to be of a high standard to limit the risk of any large-scale leak that would pose a threat to human or animal life, for example through fracture of a pipeline. If injection was into deep underground strata on land, there would be a risk, even if it could be shown to be infinitesimally small, that slow seepage could lead to a build-up of carbon dioxide in a confined space, for example beneath housing. The gain in safety therefore points towards use of geological strata beneath the seabed, some of which in the North Sea are more than 200 km from shore. These also have a far greater capacity.

3.12 An alternative way of trying to isolate the recovered carbon dioxide from the atmosphere would be to dispose of it in the deep oceans. These represent a very large natural pool of carbon (see figure 2-III), and the intention would be to bypass the constraints which limit the rate at which carbon moves into this pool under natural conditions (3.24). Rather than using pipes to inject carbon dioxide at great depths, it has been suggested that a dense enough plume of carbon dioxide-enriched seawater created at shallow depth would sink to much greater depth if the slope of the seabed is favourable and the water column is not highly stratified. Alternatively, carbon dioxide might be injected into the ocean at shallow depth at locations where natural currents will carry it to greater depth; a research project is being funded by the US, Japanese and Norwegian governments.[10] Information is needed about the possibility of environmental damage, especially the effects on marine organisms from increased carbon dioxide concentrations and increased acidity. In any event, there is considerable uncertainty whether disposal into the oceans would achieve the aim of long-term isolation, in that carbon dioxide disposed of into seawater at a depth of 3,000 m might be returned to the atmosphere within the relatively short time of 250 to 550 years.[11]

3.13 It is open to interpretation whether disposal of carbon dioxide into the ocean or under the sea-bed would be permissible under current international law. Greenpeace contends[12] that either practice would violate the London Convention on the prevention of marine pollution by dumping of wastes and other matter.[13]

3.14 In our view, injection of recovered carbon dioxide into oil and gas fields (possibly to enhance oil recovery) or into saline aquifers beneath the sea-bed would be more effective and easier to monitor, and would have less environmental impact, than disposing of it in the deep oceans.

### *INCREASING TAKE UP OF CARBON BY VEGETATION*

3.15 Another aspect of the global carbon cycle open to further human intervention is the exchange of carbon between the atmosphere and terrestrial ecosystems (figure 2-III). The limits on carbon dioxide emissions imposed under the United Nations Framework Convention on Climate Change include a country's net emissions from this source. Most of the carbon in terrestrial ecosystems is in forests, mainly in the soils in forests. Most of the remainder is in wetland soils, including peats. Table 3.1 shows how carbon is distributed between forests in different latitudes, and between the vegetation and the soils in those forests.

3.16 Most of the movement of carbon from the atmosphere into forests occurs when trees are growing to maturity (appendix D, D.26-D.27). When vegetation dies some of the carbon it contains passes into the soil, and the rest is released to the atmosphere in the form of carbon dioxide. Once the trees in a forest have reached maturity it will no longer remove a substantial net amount of carbon from the atmosphere, but nor should it become a net source. When trees die and rot, or are burnt, there should not be any net emission of carbon dioxide into the atmosphere in the medium term if new trees grow up in their place, either naturally or through human intervention. If, on the other hand, that does not happen, and the soil is cultivated or otherwise disturbed, not only will the carbon formerly contained in the trees enter the atmosphere, but a substantial part of the carbon in the soil may be released into the atmosphere in the form of carbon dioxide.

3.17 Deforestation and changes in land use have contributed to the enhancement of the greenhouse effect that has already occurred (2.7). Rapid deforestation is taking place now in many developing countries. Between 1990 and 1995 the area of forest in developed countries increased by 9 million hectares but the forest area in developing countries was reduced by about 65 million hectares. The drivers have been conversion to cultivation to support increasing human populations and unsustainable commercial logging.[14] Any consideration of the potential for increasing the take-up of carbon by vegetation as a way of countering climate change has to take into account the economic and social conditions that are currently shaping land management.

3.18 To have any significant effect on the amount of carbon taken up globally by vegetation it would be necessary to plant very large areas with trees or allow very large deforested areas to regenerate through natural succession. As it is only trees growing to maturity which take up carbon dioxide rapidly, the impact of a programme of tree-planting would depend on the length of time for which it could be maintained. To remove the amount of carbon projected to be emitted globally over the next half century from burning fossil fuels would require afforestation of an area as big as Europe from the Atlantic to the Urals.[15] The Intergovernmental Panel on Climate Change (IPCC) estimated in 1995 that a global programme up to 2050 consisting of reduced deforestation, enhanced natural regeneration in tropical countries and worldwide afforestation could take up 60-87 GtC,[16] equivalent to 12-15% of projected emissions from burning fossil fuels over that period.[17]

3.19 IPCC estimated the cost of the programme it considered as £8-13 per tonne of carbon removed from the atmosphere, depending on the region, with no discount rate applied.[18] A study of the Mexican state of Chiapas has produced much higher estimates: £30/tonne carbon with a 5% discount rate and £40/tonne carbon with a 10% discount rate.[19] Large programmes of afforestation or reforestation in themselves need careful appraisal and extensive public consultation if severe political, social and environmental problems are to be avoided. Monoculture plantations, for instance, reduce biodiversity. And afforestation in the dry tropics can lower the water tables and river flows on which people depend.

**Table 3.1**

**Carbon pool in forests and forest soils (1987-1990)**[20]

| | total carbon in forests and forest soils | | proportion of carbon in soils |
|---|---|---|---|
| | GtC | % | % |
| boreal forest (high latitudes) | 559 | 30.0 | 84 |
| temperate forest (mid latitudes) | 159 | 8.5 | 63 |
| tropical forest (low latitudes) | 1,146 | 61.5 | 50 |
| all forests | 1,864 | 100.0 | 61 |
| all terrestrial ecosystems | 2,200 | | 73 |

3.20 A crucial consideration is the impact that the higher concentration of carbon dioxide in the atmosphere and changes in climate will in themselves have on the take-up of carbon dioxide by vegetation. There is considerable uncertainty about that (appendix D, D.28), and the effects may vary between regions. In some regions of the world climate change may stimulate forest growth. Because of a large reduction in the area covered by tropical rain forest the overall effect is likely to be a reduction in the capacity of terrestrial ecosystems to take up and store carbon (2.35). The predictions of one computer model[21] which simulates the global distribution of natural vegetation as it responds to changing atmospheric carbon dioxide concentrations suggest that terrestrial ecosystems can be expected to remove 2-3 GtC a year from the atmosphere over the next half century; but thereafter increasing aridity and dieback of vegetation may convert them into a net source of some 2 GtC a year.[22]

3.21 Preserving and expanding the existing carbon storage capacity of terrestrial ecosystems can contribute to limiting the concentration of carbon dioxide in the atmosphere. Achieving that aim globally would involve a reversal of current trends, and in the long term climate change may seriously constrain the extent to which it can be achieved. In some countries which are largely forested, for example Finland,[23] forest management could largely offset emissions from burning fossil fuels. It would be unrealistic however to base policies on the assumption that this could happen globally.

3.22 The greater part of the carbon in terrestrial ecosystems is in soils rather than vegetation. Because most carbon in soils comes from vegetation, there are no measures available to produce direct increases in the amounts of carbon stored there. Because of the very large amounts of carbon dioxide and methane that could be released from soils however, the effects on soil carbon are a very important consideration in assessing the effects of land management practices on carbon dioxide emissions.

3.23 Rather than attempt to offset carbon dioxide emissions from fossil fuels by planting trees, a more robust policy may be to grow trees, shrubs or fast growing grasses in managed systems to provide a substitute for fossil fuels. If the vegetation harvested to supply energy is always replaced by new growth, the quantity of carbon dioxide taken up from the atmosphere will almost compensate for the quantity emitted when the preceding crop is burnt, and this closed cycle can continue indefinitely (3.47).

### *INCREASING TAKE UP OF CARBON BY THE OCEAN SURFACE*

3.24 Through the exchanges between the atmosphere and the oceans in the global carbon cycle (see figure 2-III) there is a net movement of carbon into the oceans, which have absorbed about 40% of the extra carbon dioxide emitted since industrialisation began (2.13). Under natural conditions the rate at which carbon moves into this pool is determined by the solubility of carbon dioxide in the surface layer of the oceans, the amount of carbon contributed by biological productivity in the surface layer, and the rate of mixing between the surface layer and deep oceanic water. Increasing the biological productivity of the surface layer can increase the amount of carbon transferred to the deep oceans and, as a result, increase the amount of carbon dioxide absorbed by the ocean surface (appendix D, D.6-D.12). For one-fifth of the oceans, in particular the Southern Ocean, the limiting factor in biological productivity is thought to be the amount of iron available. Elsewhere the limiting factor is thought to be the availability of nitrogen.

3.25 Experiments have confirmed that sprinkling iron on the ocean surface can increase productivity and the transfer of carbon from the surface layer to greater depth,[24] although it has yet to be demonstrated that the technique can be scaled up and successfully repeated. It is estimated however that, in order to reduce the atmospheric concentration of carbon dioxide by 50 parts per million by volume (ppmv), very large quantities of iron would have to be sprinkled continuously on a quarter of the world's ocean surface.[25] This could be very expensive: estimates in two studies range from £30 to £120 per tonne of carbon removed from the atmosphere.[26]

3.26 Exploitation of the biological resources of the Southern Antarctic Ocean that threatens to impair ecosystem functions is prohibited by the Convention on the Conservation of Antarctic Marine Living Resources.[27] Modelling studies suggest that artificial fertilisation of the oceans could have severe ecological consequences.[28] It is likely to reduce oxygen concentrations significantly in certain zones. As well as reducing biomass and biodiversity, that is likely to increase the amounts of other greenhouse gases such as methane and nitrous oxide released from the oceans, possibly to the point where the exercise becomes self-defeating. Although research into artificial fertilisation of oceans is expanding, particularly in the USA, we concur with IPCC's conclusion that it is not a viable method of increasing carbon uptake from the atmosphere.[29]

## CHANGING THE WAYS IN WHICH ENERGY IS OBTAINED AND USED

3.27 The scenarios discussed in chapter 2 indicate the scale of reduction in emissions from burning fossil fuels that would be necessary to stabilise the concentration of carbon dioxide in the atmosphere. To achieve stabilisation at 550 ppmv (about twice the pre-industrial level) global emissions would eventually have to be reduced to about 70% below their present level (see figure 2-VI). Although increased uptake of carbon by vegetation could in principle offset a proportion of the emissions from burning fossil fuels, there is equally the possibility that terrestrial ecosystems may be the source of further net emissions of carbon dioxide in future (3.20, 3.22). Even allowing for the possibility that carbon dioxide produced in large combustion plants might be recovered and disposed of to prevent it reaching the atmosphere, limiting the concentration of carbon dioxide in the atmosphere will clearly require more fundamental modifications in the ways the human race obtains and uses energy. We review first the scope for reducing the amounts of energy used, then the possibility of making more efficient use of fossil fuels, and finally the availability of other sources of energy that can be substituted for fossil fuels.

### *REDUCTIONS IN ENERGY USE*

3.28 The rise in carbon dioxide emissions reflects the enormous increase in energy use over the last half century (see figure 1-I). This has been the result partly of the growth in world population and partly of higher standards of living. As human societies become wealthier, an increasing variety and volume of products and services are manufactured and provided, and people travel more.[30] Electrification brings a sharp rise in energy consumption because it enables households to use a wide variety of appliances. With greater affluence, people want higher levels of illumination. They want their homes and workplaces to be warmer in winter and cooler in summer. Many coveted activities and possessions are linked to high levels of energy consumption, for example long-haul air travel and large cars.[31]

3.29 To the extent that the increase in world energy use has been driven by population growth, it could be expected to continue for much of the 21st century, even though the average energy use per person globally has come close to stabilising since the oil crisis of the 1970s (see figure 1-I). Continuing economic growth could also be expected to boost energy use. As economic growth proceeds, it becomes less energy-intensive;[32] the energy intensity of the global economy is falling.[33] IPCC's key 1995 scenario (2.20) assumed that it will continue to decline by 1% a year over the next half century. Nevertheless there continues to be a strongly positive association between economic growth and energy use.

3.30 Countries at an earlier stage of economic development (for example, China and India) still have energy intensities well above the global mean.[34] The hopes of developing countries for attaining living standards and life expectancies that became common in the developed world decades ago seem to depend on very large increases in energy consumption. Some part of the increase may be only apparent, if it involves substituting commercial supplies of energy for local sources not usually recorded in the statistics, such as dung, firewood and charcoal; but that is a declining part of the picture. The 2 billion people who still do not have electricity in their homes, including two-thirds of the rural populations of Africa, Latin America and Asia outside the former Soviet Union,[35] are being deprived of such basic necessities as refrigeration and adequate lighting. Even in wealthy countries there may be significant proportions of the population who are deprived of some of the key benefits energy brings, as illustrated by the concern about inadequate home heating for vulnerable groups in the UK (6.5-6.6).

3.31 Despite the greatly increased global demand for energy it has remained abundant and cheap. This is one of the factors that has made such rapid economic growth possible. Industries which use large amounts of energy have faced pressures to cut costs by using energy and materials more efficiently. For most firms however, and for most individuals in developed countries, the cost of energy represents a very small part of their expenditure. Like any cheap and abundant commodity, it is often used wastefully.

3.32 There are therefore cultural and attitudinal barriers to improvements in energy efficiency; we discuss in chapter 6 what effect these have in the UK. Moreover, increases in the efficiency of energy use do not automatically result in less energy being used. Some of the energy savings which could be obtained by efficiency increases will not be realised because consumers respond by making more use of the relevant service or device. For instance, if houses become better insulated, people may choose to maintain higher temperatures rather than reduce their energy consumption. Car engines have become more efficient, but that did not necessarily lead to reductions in fuel consumption because cars tended to become larger and heavier, with a much wider range of equipment.[36] Another reason why it has been argued that increased efficiency will not lead to less use of energy is that the cash savings made available as a result of increased efficiency will be spent elsewhere in the economy, raising energy demand.[37]

3.33 Nevertheless, there is very great potential for increasing the efficiency of energy use through smarter use of technology, especially in the heating and cooling of buildings and in propelling cars and other vehicles. While some of the benefits from such improvements will be taken in other ways, we do not accept the pessimistic view that they will be ineffectual or self-defeating in reducing energy use. There is also very large scope, as we illustrate below and discuss in chapter 8, for reducing the losses that occur within the energy system. These losses represent the difference between *final consumption* of energy by consumers at the end of supply chains and the considerably larger *consumption of primary energy* at or near the beginning of supply chains. To the extent that such losses within the system can be eliminated by better use of technology, energy use can be reduced without any adverse implications for human wellbeing.

3.34 It would not be realistic to base policies for reducing energy use on exhorting people to forgo the benefits of using energy, nor would it be acceptable to deny them access to essential energy services. Nonetheless, changes in behaviour, within an appropriate social, institutional and economic framework, will be a necessary component of the transition to a more sustainable energy economy. The market prices of energy sources do not necessarily reflect their substantial external effects, in particular the enhancement of the greenhouse effect in the case of fossil fuels. If the prices paid by users can begin to reflect such external costs, that can have a significant effect on their decisions. They will have a greater incentive to use energy more efficiently and to select those sources of energy that cause less environmental damage. We discuss the appropriate use of economic instruments, in a UK context, later in this report (6.149-6.169).

### *USING FOSSIL FUELS MORE EFFICIENTLY*

3.35 Another approach to reducing carbon dioxide emissions is to obtain more energy from fossil fuels in relation to the amounts of carbon dioxide produced. One way of doing that is to use a fossil fuel which has a lower carbon content in relation to its energy content, the other way is to utilise that energy content more efficiently.

3.36 Gas has a lower carbon content in relation to its energy content (14.6 kilograms per gigajoule) than oil (carbon content 18.6 kg/GJ), which in turn contains less carbon than coal (carbon content 24.1 kg/GJ).[38] Supplies of gas have expanded greatly in recent decades, and it is now being used on a rapidly increasing scale globally to generate electricity. Some experts believe that global production of oil will peak between 2010 and 2030, and then decline slowly (appendix D, D.3). Gas reserves are expected to last longer: it has been suggested that global production will not peak until 2090.[39] However it is the fossil fuel with the highest carbon content, coal, which is in the most plentiful supply. Identified global reserves of coal are sufficient for several hundred years at present rates of use. Several major countries, notably China and India, have relatively little oil or gas available in their territories but large reserves of coal.

3.37 In the short and medium term there is scope for making greater use of gas, in preference to other fossil fuels, as a way of reducing carbon dioxide emissions. However even complete substitution of gas in the processes in which coal is used at present would reduce carbon dioxide emissions from those processes by only about 40% (other things being equal), and would not in itself represent a solution to the problem of limiting carbon dioxide emissions. Moreover, in the absence of other major changes in the way the world obtains and uses energy, it would be necessary to return to the use of coal at a later date. Switching from other fossil fuels to gas could nevertheless have a useful part to play in the transition to a new energy economy.

3.38 Improvements in technology have increased the efficiency of fossil fuel generating plants. A new coal-fired generating plant typically has an efficiency of 40% in converting the energy content of the coal to electricity. A new combined cycle gas turbine typically has an efficiency of 52%. Coal can be used as fuel in a combined cycle plant if it is first gasified: plants of that type, which are not yet available commercially, are expected to have a typical efficiency of 42%.[40]

3.39 When fossil fuels are burned to generate electricity or drive internal combustion engines or gas turbines however, the efficiency with which the heat energy they produce can be converted into work is subject to a severe and fundamental physical limitation, as explained in

## BOX 3A EFFICIENCY OF ENERGY CONVERSION

**Heat engines**

Although the first law of thermodynamics states that energy can be neither created nor destroyed (see the definitions at the beginning of this report), the different forms of energy are not simply interchangeable. Converting heat to work involves using some form of heat engine in which heat enters continuously at a high temperature ($T_1$) and leaves at a low temperature ($T_2$). The maximum fraction of the heat entering which can be converted to work is

$$\eta_{max} = 1 - (T_2/T_1) = (T_1 - T_2)/T_1$$

The fraction of the heat not converted to work leaves the engine as ***low-grade heat*** at the lower temperature. The maximum possible efficiency of conversion of heat to work is sometimes termed the Carnot efficiency. This relationship is a statement of the second law of thermodynamics.

A common form of heat engine is the steam cycle, commonly used to generate electricity from fossil fuels in power stations. Heat from the burning fuel is used to produce high-temperature, high-pressure steam. The steam drives a turbine, producing work, which drives an electricity generating set. The low-grade heat is rejected, usually to cooling water, by condensing the steam to water, which is recycled within the power station and heated back to steam. Internal combustion engines and gas turbines are other types of heat engine.

The *efficiency* of the process is measured as the ratio of useful energy output (as electricity in the case of a power station) to thermal input obtained from releasing chemical energy by burning the fuel.

**Combined heat and power plants**

Combined heat and power (CHP) plants provide a way to use more of the energy released by burning a fuel. They are designed to produce energy in the two forms of electricity and low-grade heat. The latter is typically used for space heating (in buildings) or drying (in industrial applications). The overall efficiency of a CHP plant is defined as the ratio of electrical plus thermal energy output to fuel energy input.

**Heat pumps**

A heat pump is the converse of a heat engine. It uses mechanical work to ‘pump’ heat from a source at low temperature ($T_2$) to a higher temperature ($T_1$). The minimum ratio of work input to heat delivered to the higher temperature is given by the Carnot equation set out above. In the case of a heat pump

$$(\text{Work in / Heat out})_{min} = 1 - (T_2/T_1) = (T_1 - T_2)/T_1$$

The closer these two temperatures are to each other, the less work is required. Thus heat pumps are useful where relatively low grade heat is needed, at temperatures 10-20°C above that of the heat source, usually for space or water heating. In these circumstances the ratio of electrical energy consumed by a heat pump to the useful heat it delivers to a building is typically 1:3.

Heat is drawn in at the lower temperature ($T_2$) to evaporate a circulating fluid with an appropriately low boiling point. The vapour passes through a compressor which raises its pressure so that it condenses, giving up heat at the higher temperature ($T_1$). The condensed liquid passes through an expansion valve, back to the lower pressure, cooler part of the cycle. The work input to the compressor represents the work input to the heat pump.

Chemicals which are powerful greenhouse gases and/or which deplete the stratospheric ozone layer - CFCs, HCFCs and HFCs - have been used as the circulating fluid. If the use of heat pumps is to expand, then less environmentally damaging alternatives will have to be deployed.

The possible scale of operation ranges from relatively large devices contributing to heat distribution networks or industrial installations down to domestic refrigerators (in which heat is pumped from inside to the air outside). Some designs of heat pump can be operated in either direction, for example to provide heating in winter and cooling in summer. The heat source (or heat sink, when the device is used in cooling mode) can be a water stream (such as a river, or municipal wastewater), air, groundwater or soil.

**Fuel cells**

A fuel cell converts chemical energy directly to work (in the form of electrical energy) without using a heat engine. They are not subject to the Carnot efficiency limit.

box 3A. A very substantial proportion of their energy content is commonly wasted as low-grade heat. That is all the more significant for the level of carbon dioxide emissions because the most rapid growth in global demand for energy has been for electricity and mobility (1.3). Transmission and distribution of electricity involves further energy losses.

3.40 Beyond a certain point the efficiency with which the energy content of fossil fuels is utilised cannot be further improved unless the low-grade heat produced is put to use. A *combined heat and power plant* (CHP) achieves this, in that it supplies energy in both forms, heat and work. The overall conversion efficiency of such a plant varies according to the ratio of heat to power in its output, but can be as high as 70-80%.[41]

3.41 CHP plants can be sized to produce the heat and electricity required for a single building, such as an hospital or hotel, or for a manufacturing process. Prototypes have been designed that are small enough for a single house. A large CHP plant serving a number of buildings requires a *heat distribution network*, as well as an electricity distribution network. Scandinavian experience shows that a heat distribution network can extend economically for some tens of kilometres and reach tens of thousands of homes and other premises (box 8A). The heat is usually conveyed by hot water at high pressure. It is supplied to users via heat exchangers which transfer heat from the main circuit to a local medium, for example the water circulated at lower pressure through a building's central heating system.

3.42 There are some alternative technologies which are very efficient in energy terms. Fuel cells provide a method of converting chemical energy to electricity which is not subject to the thermodynamic limitation that applies to heat engines. A hydrogen fuel cell can achieve a conversion efficiency of almost 60% in generating electricity, and can also be used as a CHP plant. We discuss the potential role of fuel cells later in this report (8.62).

3.43 Another technology which is a highly efficient way of using electricity for space and water heating is the *heat pump*. This can pick up heat from a lower temperature source, generally outside a building, and deliver it at a higher temperature inside the building, thus making it possible to harness the abundant quantities of heat available from rivers, streams, wastewater, groundwater, soil and air. For reasons explained in box 3A, a heat pump typically delivers, as useful heat, 2.5 to 4 times the rate of energy it consumes in electrical power. The heat distribution network described in box 8A uses heat pumps as a major source of heat, and they can also be used to supply heat to individual buildings. We discuss later in this report, in a UK context, the need to develop a comprehensive strategy for the supply and use of heat as a vital component in policies for reducing carbon dioxide emissions (8.4-8.16).

### *SUBSTITUTING OTHER ENERGY SOURCES FOR FOSSIL FUELS*

3.44 As well as reducing carbon dioxide emissions, there are other motivations for seeking sources of energy that can provide alternatives to fossil fuels. It was always understood that reserves of fossil fuels are finite. Most countries do not have significant supplies of their own. The price increases and shortages during the oil crisis of the 1970s led many countries to take an active interest in developing more diverse sources of energy. A further motivation has been concern over the effects of other substances emitted when fossil fuels are burned (1.6-1.7). Although programmes to develop alternatives date back half a century, realisation of the threat posed by climate change has given the task much greater impetus.

3.45 The ways in which energy can be obtained without producing carbon dioxide are:

from the sun as heat, or by converting sunlight directly to electricity

from the sun indirectly, by utilising the winds caused by differences in temperature between different parts of the Earth's surface, or the wave energy arising from interaction between winds and oceans, or the water power made available inland as a result of rainfall

from gravitational forces between moon, sun and Earth, by exploiting tidal flows in estuaries or elsewhere in the oceans

from heat in the Earth's core (most easily from aquifers in which the water is at a high temperature)

by splitting atoms (nuclear fission).

3.46 In principle energy could be obtained by fusing hydrogen atoms (nuclear fusion, the process by which the sun obtains energy). Despite extensive research programmes this technology is unlikely to become available in the next half century (7.16).

3.47 There are other ways of obtaining energy which can also be beneficial in limiting the greenhouse effect, even though they give rise to emissions of carbon dioxide. Energy from the sun enables green plants to use carbon dioxide to form organic compounds (the process known as photosynthesis). The chemical bonds in these compounds represent a store of energy. The carbon dioxide which growing plants take up from the atmosphere can compensate for much of the carbon dioxide released into the atmosphere if materials derived from plants are used as a source of energy in place of fossil fuels (7.55). Although energy crops are not carbon-neutral, net emissions from their combustion represent only 5-10% of those from fossil fuels.[42]

3.48 Burning methane obtained from biological material gives rise to emissions of carbon dioxide, but does not add to the greenhouse effect if the material would otherwise have emitted carbon dioxide by decaying aerobically. The benefit is much greater if the material would otherwise have decayed anaerobically, for example in a landfill site, and emitted methane into the atmosphere, because methane is a more powerful greenhouse gas (7.57).

3.49 A rigorous comparison between the implications which different energy sources have for the greenhouse effect involves analysing not simply the processes from which energy is obtained, but whole supply chains. Before any energy source can be exploited, energy has to be used in constructing or manufacturing and installing the necessary equipment. The *energy payback period* is the length of time before the energy obtained from a source exceeds the energy that had to be used in order to exploit it. The costs of constructing an energy installation often provide a broad indication of the energy required to do so. Energy may also be used in mining fuels, in processing them (for example, in enriching uranium) or in transporting them to a generating plant (especially significant for fuels, such as crops, which have a low energy density); in transporting, treating and disposing of any wastes produced; or in decommissioning power stations or other equipment. The extent to which energy use elsewhere in a supply chain gives rise to carbon dioxide emissions depends on the sources from which that energy is obtained. If fossil fuels become progressively less important as an energy source for electricity generation, for example, energy use elsewhere in supply chains will become less important as a contributor to carbon dioxide emissions.

3.50 Comparative analyses of entire life cycles of energy sources, based on current patterns of energy supply, confirm that the carbon dioxide emissions attributable to electricity generation using some key renewable sources are an order of magnitude, sometimes two orders of magnitude, lower than the emissions attributable to electricity generation at a modern fossil fuel plant.[43] The margin of difference is smaller for photovoltaic cells because of the amounts of energy used in their manufacture.[44] The carbon dioxide emissions attributable to electricity generation at a nuclear power station are also far lower than in the case of a modern fossil fuel plant.[45]

3.51 Countries differ in their endowments of renewable energy sources. The UK has less solar power available than many other countries, and much less inland water power than some. On the other hand it has very large resources of wind and wave power, and substantial power available in tides. Countries also differ in the extent to which they are committed to using nuclear power.

3.52 There is general agreement that the large-scale development of alternatives to fossil fuels must be a central part of the response to the challenge of climate change. A key scenario in IPCC's 1995 assessment assumed that the amount of power obtained from 'carbon-emission-free' sources in 2050 will be equivalent to all current energy sources combined (2.20). There are strong disagreements however about whether the emphasis should be on renewable energy sources or on nuclear power. Some have contended that 10% of the world's electricity could be provided from wind power by 2020.[46] What is clear is that providing alternatives to fossil fuels, while at the same time keeping pace with an increasing global demand for energy, will require very large programmes of investment and construction, both in developed and in developing countries. Some of the technologies involved are complex or at an early stage of development. That points to a need to ensure there are adequate programmes of research and development. Many developing countries will also require considerable technical and financial assistance if they are to develop their energy systems in the ways that will cause least damage to the environment.

## Conclusion

3.53 Climate change is the outcome of processes that operate globally, and can be countered only through concerted international action. This review of possible preventive measures has confirmed that the measures required to limit the concentration of carbon dioxide in the atmosphere will in all probability be taken by national governments. It is unlikely that international agreements will prescribe the detailed form of such measures, as distinct from the results they are required to achieve in reducing emissions. Consideration of their potential and practicability is nevertheless an essential basis for discussing, in chapter 4, how a general international agreement to counter climate change might be reached and the position the UK should adopt in negotiations.

3.54 Any measure for limiting the concentration in the atmosphere of carbon dioxide or any other greenhouse gas will have to be safe, legal under national and international law, cost-effective, and politically and socially acceptable. Of the approaches considered in this chapter, we do not consider that attempting to increase the take-up of carbon dioxide by the ocean surface is worth pursuing (3.24-3.26). Nor would we support disposal of recovered carbon dioxide into the deep oceans (3.12). Given the extent to which the human race has already modified the global carbon cycle over the last two centuries, further interventions in the cycle designed to reverse or halt those effects can be justified only if there are grounds for confidence that they will not in themselves have major, unintended environmental impacts.

3.55 Naive suggestions are often made that climate change can be countered by planting more trees. Managing land use so as to preserve and expand the carbon storage capacity of terrestrial ecosystems is a necessary element in policies to limit the concentration of carbon dioxide in the atmosphere. In practice however there may be significant overall losses globally, in the medium term as a result of social and economic pressures (3.17), and in the long term through some of the effects of climate change (3.20). At best, human management of this pool could never offset the current level of global emissions from burning fossil fuels. And in the event what happens to it may exacerbate the effect of those emissions.

3.56 Recovering carbon dioxide produced when fossil fuels are burnt and disposing of it in deep underground strata has promise. Familiar technologies can be used, and for north-west Europe the strata used would probably be under the sea-bed. There is good reason to believe that carbon dioxide injected into offshore aquifers would remain isolated from the atmosphere and not pose a threat to terrestrial or marine organisms (3.10). Although recovering and disposing of carbon dioxide would add considerably to the cost of generating electricity from fossil fuels, it could still be cheaper than using plant material to generate electricity.[47] Whether disposal of the recovered carbon dioxide under the sea-bed would constitute waste disposal and contravene current international law has been discussed by the parties to the London Convention, and no decision has been taken (3.13). It remains to be seen whether such an approach would be socially acceptable.

3.57 The major limitation of the approach discussed in the previous paragraph is that it is not suitable for small installations or dispersed energy uses. Even if it proves to be socially and legally acceptable therefore it could never be a complete answer to the problem of limiting the concentration of carbon dioxide in the atmosphere. The primary methods for doing so must be more fundamental modifications in the ways the human race obtains and uses energy. The themes introduced in the second half of this chapter are explored in much greater detail in the examination of UK policies in part II of our report. The scope for reducing energy use is discussed in chapter 6, the scope for substituting other energy sources for fossil fuels in chapter 7, and the scope for increasing the overall efficiency of the energy system in chapter 8. In chapter 9 we consider the respective contributions these approaches might make to reducing the UK's carbon dioxide emissions.

> ***The core of a global response to the threat of climate change must be the most effective and reliable forms of action, those which reduce the amounts of carbon dioxide produced by burning fossil fuels. Some contribution might be made by recovering some of that carbon dioxide and disposing of it in underground strata. The more the carbon storage capacity of terrestrial ecosystems can be preserved, and if possible expanded, the less daunting the challenge of reducing carbon dioxide emissions will be***