

Appendix D

CARBON RESOURCES AND REMOVAL: TECHNICAL ISSUES

GLOBAL FOSSIL FUEL RESERVES AND RESOURCES

D.1 The limitation on our use of fossil fuels is unlikely to be the size of the available reserves of such fuels, but the degree to which their combustion leads to global warming by increasing the level of carbon dioxide in the atmosphere. The predominant view among scientists is that fossil fuels (coal, oil and natural gas) are, as that name presupposes, the outcome of biological processes in the distant geological past. For a meaningful discussion concerning quantities of fossil fuels, a number of terms need to be defined. The term ‘reserves’ refers to fossil fuels whose location is known and which can be recovered under certain assumptions concerning the available technology and the maximum price of the commodity. By contrast, ‘resources’ refers to the total amount of recoverable fossil fuel (identified reserves plus that which is yet to be found). Advances in technology increase the estimates of reserves as a proportion of total fossil fuel resources.

D.2 Oil companies have a detailed understanding of the geological conditions associated with oil deposits, which enables them to predict in which regions they are likely to occur. The world has been extensively mapped for large oil deposits which has led to a low and declining rate of discovery. No super-giant oil fields have been found for nearly a decade, and giant field discoveries have been in decline since 1970.¹

D.3 There are differences of opinion about the size of the global oil ultimate, the quantity of oil that will ultimately be accessible to human exploitation. Pessimistic estimates of the conventional (non-heavy, low viscosity, easily recovered oil) global oil ultimate based on oil industry data are 2,000 Gb (gigabarrels), implying that global oil production will peak between 2010 and 2030. Over and above this, there is an estimated further 4,000 Gb of oil in the same deposits which cannot be extracted using current recovery techniques, but may be accessible due to improvements in technology. There are a further 3,000-4,000 Gb of heavy oil which would be much more expensive than the currently exploited deposits to extract and refine, in terms of both money and the requirement for energy.² Higher estimates for the global oil ultimate of 3,000 Gb, based on the utilisation of non-conventional oil reserves and improved technology for non-conventional oil production, might allow the peak for global production to be deferred until 2060.³

D.4 Natural gas (methane) reserves are likely to be available for exploitation for a longer period than oil reserves. It has been suggested that peak global production would not occur until 2090.⁴ Identified global coal reserves are sufficient for over two hundred years at present rates of use.⁵ There is a very large resource of methane on the deep ocean bed in the form of frozen methane hydrate,⁶ but the technology to exploit that has yet to be developed.

D.5 Estimates of total global fossil fuel ‘reserves’ are between 829⁷ and 1,501⁸ GtC whilst total fossil fuel resource estimates (excluding methane hydrates) range from 4,166 to 4,678 GtC.

ENHANCING OCEAN SURFACE UPTAKE OF CARBON DIOXIDE

D.6 Changes in productivity of the oceans have in the past been major drivers of change in atmospheric carbon dioxide concentration. The world's oceans currently store approximately 40,000 GtC and exchange approximately 90 GtC with the atmosphere each year (see Figure 2-III).⁹ Although the oceans have the theoretical capacity to absorb all anthropogenic carbon dioxide, this could only be achieved over a time-scale of several thousand years.

D.7 Although the surface layer of the ocean is saturated with carbon dioxide, the deeper ocean is not in equilibrium with atmospheric carbon dioxide, the limiting factor being the rate of carbon transfer between surface waters and the deep ocean. There are two ways in which carbon dioxide is transferred from the surface to the deep ocean; by mixing and the sinking of dead marine organisms which have taken up carbon from surface waters, and which are ultimately buried in ocean bottom sediments. The latter process, which has been referred to as the *biological pump*, can be promoted by fertilising the ocean with iron or macro-nutrients (nitrogen, phosphorous and silicon) to increase algal primary productivity.

D.8 One fifth of the world's oceans have 'high-nutrient-low-chlorophyll' (HNLC) waters in which it has been suggested that algal growth is limited by the availability of iron. Iron fertilisation experiments in the three main HNLC regions (the Equatorial Pacific, the Sub-Arctic Pacific and the Southern Ocean) demonstrated increased rates of algal productivity.^{10, 11}

D.9 The effectiveness of biological productivity as a method of removing carbon from the atmosphere would also depend on the circulation patterns within the oceans. Circulation between surface and subsurface water in the Southern Ocean is relatively rapid.¹² As the Southern Ocean maintains a large pool of unused nutrients, it represents the most promising gateway for the transfer of carbon between the atmosphere and deep ocean. Modelling studies have suggested that the Southern Ocean plays a dominant role in maintaining natural levels of atmospheric carbon dioxide and that variations in iron availability in the geological past (through atmospheric dust transport) may have influenced glacial-interglacial variations in carbon dioxide levels.¹³ Evidence advanced in support of this hypothesis includes analysis of ice cores, in which inferred elevated levels of atmospheric iron correlated with low atmospheric concentrations of carbon dioxide.¹⁴

D.10 The major limiting factor for algal growth throughout the remainder of the world's oceans is the availability of nitrogen. An objective for research has been to test the feasibility of establishing large kelp farms in the oceans through the addition of nutrients. Modelling studies have indicated that attempts to increase carbon uptake in this way would be expensive and inefficient.¹⁵ In addition, there may be significant environmental impacts such as reduced biodiversity in surface waters, changes in community structure, the creation of oxygen deficient waters, and the generation of other greenhouse gases.

D.11 Although it has been suggested that iron fertilisation in the Southern Ocean has the potential to lower atmospheric carbon dioxide levels by 6-21%¹⁶, the critical factor being the rate of vertical mixing, the IPCC¹⁷ concluded that this was not a viable method for carbon sequestration. It would require fertilisation of 25% of the world's ocean continuously and indefinitely and even if it was entirely successful, would only reduce atmospheric carbon dioxide levels by 50 ppmv.¹⁸

D.12 Although further studies of nutrient fertilisation of oceans are planned, there are large uncertainties about the costs of deploying these methods on a large-scale. Estimates from two studies range from £30 to £120 per tonne of carbon.^{19, 20} Verification of the impact of iron fertilisation would be particularly challenging bearing in mind the remote location of the Southern Ocean, where ocean fertilisation would be undertaken.

CAPTURING AND ISOLATING CARBON DIOXIDE FROM FOSSIL FUEL COMBUSTION

REMOVAL OF CARBON FROM FOSSIL FUELS BEFORE OR DURING COMBUSTION

D.13 Methods for separating carbon from fossil fuels before their combustion have recently been identified. In the case of natural gas, the options for making a carbon-free fuel include steam reforming or partial oxidation, creating an intermediate, hydrogen-rich gas which is then burnt to produce electricity.²¹ Equivalent schemes have been recognised for use with coal fuel.²² In the case of natural gas, it is assumed that a minimum of 85% of carbon dioxide would be captured, although higher levels of capture are possible. Further development of turbines which can burn hydrogen-rich mixtures is required.²³ In addition to the extra cost of removing carbon from the fuel, there would be the additional cost of its subsequent storage (see below).

D.14 A recent, novel strategy for coal-fired power plants is the use of enriched oxygen combustion with flue gas recycling which produces a high purity stream of carbon dioxide. Its benefits over other systems designed to avoid carbon dioxide emissions include a high (up to 95%) concentration of carbon dioxide in dry flue gases.²⁴

TECHNIQUES FOR REMOVING CARBON DIOXIDE FROM FLUE GASES

D.15 Technologies have been developed to remove carbon dioxide from natural gas fields in which it occurs in very high proportions in order that the gases can be marketed commercially. With suitable modifications these end-of-pipe technologies (which are described in detail below) can be applied to the removal of carbon dioxide from the flue gases of plants burning fossil fuels. These options are expensive; they may increase the cost of generating electricity by up to 50% where the fuel is natural gas and up to 80% where the fuel is coal. Moreover their energy requirements typically reduce the overall efficiency of generation by about 10%.²⁵

D.16 Membrane separation (for most types of power plant, gas absorption membranes) seems to represent the best approach in terms of power requirements, carbon dioxide removed and the cost of emissions avoided; but much further development is necessary before it could be used on a large scale in power plants. Combinations of techniques may well have advantages, for example using membranes to remove most of the carbon dioxide and a chemical solvent to remove the remainder. Cryogenic distillation has the advantage of producing carbon dioxide in liquid form, suitable for transportation; and other approaches could be used to produce the high initial concentration of carbon dioxide which this process requires. However, it is likely to be prohibitively expensive.

D.17 Chemical absorption using monoethanolamine as the solvent is a proven method for removing carbon dioxide from the flue gases of conventional power plants. In integrated gasification combined cycle (IGCC) plants, in which the flue gases are at high pressure and have relatively low concentrations of inert gases, physical absorption using dimethyl ether or polyethylene glycol is more suitable, and requires relatively little extra energy.

D.18 There are three main options for removing carbon dioxide from flue gases:

absorption (captures 82-99% of carbon dioxide with a purity of at least 96%, and often more than 99%): physical or chemical solvents are used to scrub the flue gases and collect the carbon dioxide; heat is then applied to the resulting compound in order to recover the carbon dioxide and regenerate the solvent. The choice of solvent represents a compromise between carrying capacity and energy requirement for regeneration.

adsorption (captures 95% of carbon dioxide but purity ranges from 50% to 97%): carbon dioxide is attracted physically or chemically to sites on a suitable solid; the carbon dioxide is recovered and the solid regenerated either by raising the temperature or by reducing the pressure.

gas separation membranes utilise the physical and chemical interactions between the gases and the membrane material. Because of poor selectivity it is usually necessary to recycle the gases through the membrane or provide several stages, and the carbon dioxide obtained may be very impure. In the gas absorption membrane approach, a hydrophobic membrane is used to bring the flue gases into contact with an absorbent liquid, such as a sulphite, carbonate or amine solution. The process is highly selective, and performance can be further improved by adding a suitable solvent to the liquid. Use of metal oxide gels may lead to improvements in adsorption and membrane technologies.

DISPOSAL INTO DEEP UNDERGROUND STRATA

D.19 The natural pore spaces in underground rock strata have the capacity to store large amounts of carbon dioxide separated from flue gases following the combustion of fossil fuels. Compressed flue gases from a coal-fired power station with a carbon dioxide content of 15% would require about 68 m³ of storage space per tonne. However, if disposed at depths in excess of about 800 m, pressure and temperature conditions are such that carbon dioxide would be in a supercritical liquid state and only require 1.3 m³ of storage space per tonne. Carbon dioxide stored in such formations would be isolated for long periods of geological time from the atmospheric reservoir. Such depths are much greater than the normal depths of fresh, potable groundwater aquifers, which are normally restricted to within 200 m of the Earth's surface.

D.20 There are four main geological settings appropriate for deep storage: oil and gas fields (preferably disused), deep rocks containing saline waters and unmineable coal formations. Such formations occur both beneath the land surface and the sea.

D.21 Exploitation of a (methane) gas field normally extracts up to 95% of the available gas. If disposal were started soon after field abandonment, almost all of the space vacated by methane could be occupied by carbon dioxide before the original, natural field pressure was reached. The fact that in such fields gases lighter than the disposed carbon dioxide have been confined naturally for millions of years provides evidence for the long-term integrity of storage. In the Sleipner Vest field in the North Sea, natural gas contains up to 9.5% of carbon dioxide. In order to comply with the sales gas specification this must be reduced to below 2.5%, which is achieved by capturing carbon dioxide from the high pressure produced gas by amine scrubbing and re-injecting it into the Utsira formation, a saline aquifer above the natural gas reservoir (see box E).²⁶

D.22 Disposal of carbon dioxide in oil fields can be achieved during the process of enhanced oil recovery (EOR). After readily extracted oil has been pumped from a field, carbon dioxide can be injected to change the residual properties of the remaining oil making it easier to extract.

BOX D**CAPTURE OF CARBON DIOXIDE AND RE-INJECTION
INTO A SUB-SEA AQUIFER**

The Sleipner field is in the Norwegian sector of the North Sea and is one of the largest fields for natural gas production. It has a naturally high carbon dioxide content of 9% which to meet export specifications has to be reduced to 2.5%, producing 1 million tonnes of carbon dioxide per year. If released to the atmosphere it would increase Norway's carbon dioxide emissions by about 3%. Since 1996, the company exploiting the gas field (Statoil) has captured and injected 1 million tonnes of carbon dioxide a year into an aquifer 1,000 m beneath the sea bed.

Carbon dioxide is absorbed by amine in a contact tower and separated from the absorbent in another tower. The captured carbon dioxide is injected into a porous sandstone aquifer (the Utsira Formation) approximately 1,000 m beneath the sea-bed. Overlying the Utsira Formation is the Hordaland shale which acts as an impermeable barrier preventing carbon dioxide leaking to the atmosphere. Geophysical techniques have been used to delineate the plume of carbon dioxide and to verify that it has not escaped back to the surface.

This is the largest current industrial use for carbon dioxide. In most cases, carbon dioxide used for this purpose comes from natural underground sources. In the USA it is transported by pipeline for up to 800 km. Some carbon dioxide used for EOR in the USA is obtained from flue gases, and this source could more generally be substituted for natural carbon dioxide. Although the economic viability of EOR and the disposal of carbon dioxide by this route depends on the price of oil, which if depressed, would inhibit its use, it is significantly more economically viable than most other carbon sequestration options. Injection of carbon dioxide derived from existing fossil energy use (and retention underground) has the effect of reducing the net emissions of carbon dioxide produced from burning the oil recovered by this technique. The time period over which there would be environmental advantages in injecting carbon dioxide into an oil field for EOR may therefore be short, say five years. It has been estimated that European offshore oil fields have the capacity to dispose of about 1.6 GtC²⁷ (equivalent to 6 years of European carbon dioxide emissions from thermal power generation in 1990) and that there is a global disposal capacity of 16.6 GtC.²⁸ There is a large potential market for EOR in the USA and Canada, the latter having been estimated as 277 MtC over 15 years.²⁹

D.23 Deep, extensive reservoirs of saline groundwater into which carbon dioxide could be pumped and which have traps inhibiting escape are much more common than oil or gas fields. The emissions from a 500 MW pulverised fuel-fired power station with flue gas desulphurisation could be disposed of into a deep North Sea reservoir through six wells.³⁰ A scheme to dispose of the carbon dioxide contained in a gas field into saline reservoirs 900 m beneath the bed of the Natuna Sea in Indonesia is currently under consideration. It is planned to dispose of about 1.6 GtC over a 17 year period.

D.24 Potential environmental impacts associated with disposal are sub-surface pressure increases which might stimulate seismic activity, expulsion onto the sea bed of saline groundwaters (although ecological effects are likely to be minimal in an already saline marine environment), geochemical interactions between injected carbon dioxide and host rocks, subsidence or uplift of the sea bed and escape of carbon dioxide to the surface. Most of these impacts can be evaluated from evidence of behaviour of fluids in the sub-surface over long

Appendix D

periods of geological time, from the practice of extraction and fluid injection in groundwater and hydrocarbon exploitation over many decades and from current projects for underground disposal of carbon dioxide. International monitoring of current disposal schemes will help to establish whether deep disposal is a safe and reliable mitigation option.

D.25 Deep, unmineable coal formations are a potential source of natural gas in the form of methane. The injection of carbon dioxide, which has a greater affinity for adsorption helps displace the methane trapped in the coal. The technique has the advantage of more than doubling methane recovery compared to primary pressure depletion techniques. However, further research is required before the potential of this disposal route to make a significant contribution to limiting atmospheric carbon dioxide concentrations can be evaluated. Detailed research is required to verify the capacity, stability and permanence of carbon dioxide storage. However, at one demonstration project in the San Juan Basin (USA), 3 million cubic feet of carbon dioxide per day have been injected into a formation through four injection wells over a three-year period. The sale of the extra methane derived from deep coal formations would reduce net carbon dioxide storage costs. However, the release of carbon dioxide following increased methane production and combustion would have to be offset against storage savings in the overall assessment of this carbon sequestration option.

TERRESTRIAL ECOSYSTEMS IN THE GLOBAL CARBON CYCLE

D.26 The net exchange of carbon dioxide by a terrestrial ecosystem is the difference between the amount of carbon taken up in photosynthesis by the vegetation and the amount released in plant respiration, both day and night, plus the amount leaving the soil as a result of the oxidation of organic detritus derived from the vegetation and the associated respiration of the soil fauna and micro-organisms. The rate of uptake of carbon dioxide in photosynthesis is likely to be highest when the trees are young and growing fast: the loss of carbon in respiratory oxidative processes is not independent of the uptake. Both uptake and loss of carbon are functions of environmental variables including solar radiation, temperature and the availability of nutrients, nitrogen in particular, and of water.

D.27 The net ecosystem exchange (NEE) of carbon dioxide between forests and the atmosphere is currently being measured in about 70 forest stands predominantly in Europe and North America, but with some stands in Brazil, Russia, Siberia, Japan, Australia and Southern Africa. Where NEE has been measured for more than one year, the annual exchange ranges between a loss of 1 tC per hectare to a gain of 8 tC per hectare. Net losses have been found in only very few sites and these comprise old growth stands and stands on the northern fringe of the boreal forest. Values of NEE range from -1 to $+2.5$ for the boreal forest, 1 to 8 for temperate forest and 2 to 5 tC per hectare for tropical forest.³¹ This carbon is stored both in the increasing mass of the trees and in the soil. The great virtue of carbon storage in the soil is its long residence time (defined as stock of carbon/rate of supply of carbon) which, in an equilibrium situation, is of the order of 100 years for soil compared with about ten years for the tree biomass. Currently it is difficult to determine from carbon budgets (with any degree of precision, for any forest) whether the stock of carbon in the soil is increasing or decreasing.³²

D.28 It is more difficult to predict the net impact of global warming on the carbon balance of forests. On the positive side there is evidence that increased atmospheric carbon dioxide concentrations are enhancing carbon dioxide uptake by vegetation, because of increased photosynthetic rates and leaf areas and, particularly at high latitudes, increased length of the growing season. In addition, human activity has increased global nitrogen deposition³³ and

fixation³⁴ leading to global nitrogen-induced carbon sequestration in forests, estimated to range from about 0.1 to 2.3 GtC per year. On the negative side, it has been suggested that higher temperatures may increase the loss of carbon dioxide in respiration and oxidation of soil carbon, thus offsetting some of the gains in photosynthesis. However, there is considerable uncertainty in this regard.

D.29 Results from recent soil warming experiments have indicated that a rise in soil temperature of 5°C does not lead to a long-term increase in carbon dioxide loss.³⁵ The increase in atmospheric carbon dioxide concentration and the increasing incidence of drought both reduce carbon dioxide uptake and loss of water by inducing closure of the stomata (the carbon intake valves) with the result that the efficiency of photosynthesis with respect to water use increases. A lowering of ground water levels, particularly in boreal forests, may also lead to enhanced carbon release through the oxidation of soil organic matter. In boreal peatlands, lower water tables lead to the oxidation of methane to carbon dioxide, which upon release has a lower net global warming potential.

References

1. Oral Evidence from the Reading University Oil Group, 6 May 1999.
2. Oral Evidence from the Reading University Oil Group, 6 May 1999.
3. Oral evidence from Professor Odell, 6 May 1999.
4. Oral evidence from Professor Odell, 6 May 1999.
5. World Coal Institute (1998) *Coal Facts*. World Coal Institute.
6. Some estimates suggest that the global methane hydrate resource exceeds all other fossil fuel resources combined. United States Geological Survey (1992). *Gas (Methane) Hydrates – A new frontier*. <http://marine.usgs.gov/fact-sheet/methane-hydrates/title.html>
7. World Energy Council (1993). *Energy for Tomorrow's World – The realities, the real options and the agenda for achievement*. St. Martin's Press.
8. Rogner, H.H. (1997). *Climate Change Assessments: Technology learning and fossil fuels – How much carbon can be mobilized?* Paper presented to International Energy Agency Workshop on climate change damages and the benefits of mitigation, 26-28 February 1997, International Institute for Applied Systems Analysis (IIASA).
9. Intergovernmental Panel on Climate Change (1996). *Climate Change 1995: The science of climate change*. Cambridge University Press, Cambridge.
10. Cooper, D.J., Watson, A.J. and Nightingale, P.D. (1996). Large decreases in ocean-surface CO₂ fugacity in response to *in situ* iron fertilization. *Nature*, **383**, 511-513.
11. Turner, S.M., Nightingale, P.D., Spokes, L.D., Liddicoat, M.I. and Liss, P.S. (1996). Increased dimethyl sulphide concentrations in sea water from *in situ* iron enrichment. *Nature*, **383**, 513-517.
12. Siegenthaler, U. and Sarmiento, J.L. (1993). Atmospheric carbon dioxide and the ocean. *Nature*, **365**, 119-125.
13. Sarmiento, J.L. and Toggweiler, J.R. (1984). A new model for the role of the oceans in determining atmospheric P_{CO₂}. *Nature*, **308**, 621-624.
14. Martin, J. (1990). Glacial-interglacial CO₂ change: The Iron Hypothesis. *Palaeoceanography*, **5**, 1-13.
15. Orr, J.C. and Sarmiento, J. L. (1992). Potential of marine macroalgae as a sink for CO₂: constraints from a 3-D general circulation model of the global ocean. *Water, Air and Soil Pollution*, **64**, 405-421.
16. Ormerod, B. and Angel, M. (1998). *Ocean fertilisation as a CO₂ sequestration option*. IEA Greenhouse Gas R&D Programme, Cheltenham.
17. IPCC (1996).
18. IPCC (1996).

Appendix D

19. Ritschard, R.L. (1992). Marine Algae as a CO₂ sink. *Water, Air and Soil Pollution*. **64**, 289-303.
20. Ormerod, B. and Angel, M. (1998)
21. Freund, P. and Thambimuthu, K.V. (1999). Options for Decarbonising Fossil Energy Supplies. *Combustion Canada '99*, 26-28 May 1999, Calgary, Alberta, Canada; <http://www.ieagreen.org.uk/comb99.htm>
22. Goldthorpe, S.H., Cross, P.J.I. and Davison, J.E. (1992). Studies on CO₂ abatement from power plants. *Energy Conversion and Management*, **33**, 459-466.
23. Freund, P. and Thambimuthu, K.V. (1999).
24. Croiset, E. and Thambimuthu, K.V. (1999). A novel strategy for greenhouse gas abatement in coal-fired power plants: enriched oxygen combustion. *Combustion Canada '99*, 26-28 May 1999, Calgary, Alberta, Canada.
25. International Energy Agency Greenhouse Gas Programme (IEAGGP) (1994). Carbon dioxide capture from power stations. Cheltenham.
26. The oil industry also has experience of injecting mixtures of carbon dioxide and naturally occurring hydrogen sulphide, the primary objective being safe disposal of the hydrogen sulphide (information supplied by Dr. K. Thambimuthu, February 2000).
27. Holloway, S. *et al.* (1996). *The underground disposal of carbon dioxide: Summary report*. British Geological Survey, Keyworth, Nottingham.
28. IEAGGP. (1995). *Carbon dioxide utilisation*. Cheltenham, UK.
29. Croiset, E. and Thambimuthu, K.V. (1999).
30. Van der Meer, L.H.H. (1992). Investigations regarding the storage of carbon-dioxide in aquifers in the Netherlands. *Energy Conversion and Management*, **33**, 611-618.
31. Malhi, Y., Baldocchi, D.D. and Jarvis, P.G. (1999) The carbon balance of tropical temperate and boreal forests. *Plant, Cell and Environment*, **22**, 715-740.
32. Malhi, Y. *et al.* (1999).
33. Vitousek, P.K. (1997). Human alteration of the global nitrogen cycle: sources and consequences. *Ecological Applications*, **7**, 737-750.
34. Galloway, J.N., Schlesinger, W.H., Levy, H.H., Michaels, A. and Schnoor, J.L. (1995). Nitrogen fixation: anthropogenic enhancement-environmental response. *Global Biogeochemical Cycles*, **9**, 235-252.
35. From the data of Professor Linder; information supplied by Professor Paul Jarvis, March 2000.