1. Introduction

Coordinating Lead Author
Paul Freund (United Kingdom)

Lead Authors
Anthony Adegbulugbe (Nigeria), Øyvind Christophersen (Norway), Hisashi Ishitani (Japan), William Moomaw (United States), Jose Moreira (Brazil)

Review Editors
Eduardo Calvo (Peru), Eberhard Jochem (Germany)

CONTENTS

Executive Summary

According to IPCC's Third Assessment Report:
- 'There is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities.
- Human influences are expected to continue to change atmospheric composition throughout the 21st century.'

The greenhouse gas making the largest contribution from human activities is carbon dioxide (CO_2). It is released by burning fossil fuels and biomass as a fuel; from the burning, for example, of forests during land clearance; and by certain industrial and resource extraction processes.
- 'Emissions of CO_2 due to fossil fuel burning are virtually certain to be the dominant influence on the trends in atmospheric CO_2 concentration during the 21st century.
- Global average temperatures and sea level are projected to rise under all (…) scenarios.'

The ultimate objective of the UN Framework Convention on Climate Change, which has been accepted by 189 nations, is to achieve '(…) stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system', although a specific level has yet to be agreed.

Technological options for reducing net CO_2 emissions to the atmosphere include:
- reducing energy consumption, for example by increasing the efficiency of energy conversion and/or utilization (including enhancing less energy-intensive economic activities);
- switching to less carbon intensive fuels, for example natural gas instead of coal;
- increasing the use of renewable energy sources or nuclear energy, each of which emits little or no net CO_2;
- sequestering CO_2 by enhancing biological absorption capacity in forests and soils;
- capturing and storing CO_2 chemically or physically.

The first four technological options were covered in earlier IPCC reports; the fifth option, the subject of this report, is carbon dioxide capture and storage (CCS). In this approach, CO_2 arising from the combustion of fossil and/or renewable fuels and from processing industries would be captured and stored away from the atmosphere for a very long period of time. This report analyzes the current state of knowledge about the scientific and technical, economic and policy dimensions of this option, in order to allow it to be considered in relation to other options for mitigating climate change.

At present, the global concentration of CO_2 in the atmosphere is increasing. If recent trends in global CO_2 emissions continue, the world will not be on a path towards stabilization of greenhouse gas concentrations. Between 1995 and 2001, average global CO_2 emissions grew at a rate of 1.4% per year, which is slower than the growth in use of primary energy but higher than the growth in CO_2 emissions in the previous 5 years. Electric-power generation remains the single largest source of CO_2 emissions, emitting as much CO_2 as the rest of the industrial sector combined, while the transport sector is the fastest-growing source of CO_2 emissions. So meeting the ultimate goal of the UNFCCC will require measures to reduce emissions, including the further deployment of existing and new technologies.

The extent of emissions reduction required will depend on the rate of emissions and the atmospheric concentration target. The lower the chosen stabilization concentration and the higher the rate of emissions expected in the absence of mitigation measures, the larger must be the reduction in emissions and the earlier that it must occur. In many of the models that IPCC has considered, stabilization at a level of 550 ppmv of CO_2 in the atmosphere would require a reduction in global emissions by 2100 of 7–70% compared with current rates. Lower concentrations would require even greater reductions. Achieving this cost-effectively will be easier if we can choose flexibly from a broad portfolio of technology options of the kind described above.

The purpose of this report is to assess the characteristics of CO_2 capture and storage as part of a portfolio of this kind. There are three main components of the process: capturing CO_2, for example by separating it from the flue gas stream of a fuel combustion system and compressing it to a high pressure; transporting it to the storage site; and storing it. CO_2 storage will need to be done in quantities of gigatonnes of CO_2 per year to make a significant contribution to the mitigation of climate change, although the capture and storage of smaller amounts, at costs similar to or lower than alternatives, would make a useful contribution to lowering emissions. Several types of storage reservoir may provide storage capacities of this magnitude. In some cases, the injection of CO_2 into oil and gas fields could lead to the enhanced production of hydrocarbons, which would help to offset the cost. CO_2 capture technology could be applied to electric-power generation facilities and other large industrial sources of emissions; it could also be applied in the manufacture of hydrogen as an energy carrier. Most stages of the process build on known technology developed for other purposes.

There are many factors that must be considered when deciding what role CO_2 capture and storage could play in mitigating climate change. These include the cost and capacity of emission reduction relative to, or in combination with, other options, the resulting increase in demand for primary energy sources, the range of applicability, and the technical risk. Other important factors are the social and environmental consequences, the safety of the technology, the security of storage and ease of monitoring and verification, and the extent of opportunities to transfer the technology to developing countries. Many of these features are interlinked. Some aspects are more amenable to rigorous evaluation than others. For example, the literature about the societal aspects of this new mitigation option is limited. Public attitudes, which are influenced by many factors, including how judgements are made about the technology, will also exert an important influence on its application. All of these aspects are discussed in this report.

1.1 Background to the report

IPCC's Third Assessment Report stated 'there is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities'. It went on to point out that 'human influences will continue to change atmospheric composition throughout the 21st century' (IPCC, 2001c). Carbon dioxide (CO_2) is the greenhouse gas that makes the largest contribution from human activities. It is released into the atmosphere by: the combustion of fossil fuels such as coal, oil or natural gas, and renewable fuels like biomass; by the burning of, for example, forests during land clearance; and from certain industrial and resource extraction processes. As a result 'emissions of CO_2 due to fossil fuel burning are virtually certain to be the dominant influence on the trends in atmospheric CO_2 concentration during the 21st century' and 'global average temperatures and sea level are projected to rise under all … scenarios' (IPCC, 2001c).

The UN Framework Convention on Climate Change (UNFCCC), which has been ratified by 189 nations and has now gone into force, asserts that the world should achieve an atmospheric concentration of greenhouse gases (GHGs) that would prevent 'dangerous anthropogenic interference with the climate system' (UNFCCC, 1992), although the specific level of atmospheric concentrations has not yet been quantified. Technological options for reducing anthropogenic emissions[1] of CO_2 include (1) reducing the use of fossil fuels (2) substituting less carbon-intensive fossil fuels for more carbon-intensive fuels (3) replacing fossil fuel technologies with near-zero-carbon alternatives and (4) enhancing the absorption of atmospheric CO_2 by natural systems. In this report, the Intergovernmental Panel on Climate Change (IPCC) explores an additional option: Carbon Dioxide Capture and Storage (CCS)[2]. This report will analyze the current state of knowledge in order to understand the technical, economic and policy dimensions of this climate change mitigation option and make it possible to consider it in context with other options.

1.1.1 What is CO_2 capture and storage?

CO_2 capture and storage involves capturing the CO_2 arising from the combustion of fossil fuels, as in power generation, or from the preparation of fossil fuels, as in natural-gas processing. It can also be applied to the combustion of biomass-based fuels and in certain industrial processes, such as the production of hydrogen, ammonia, iron and steel, or cement. Capturing CO_2 involves separating the CO_2 from some other gases[3]. The CO_2 must then be transported to a storage site where it will be stored away from the atmosphere for a very long time (IPCC, 2001a). In order to have a significant effect on atmospheric concentrations of CO_2, storage reservoirs would have to be large relative to annual emissions.

1.1.2 Why a special report on CO_2 capture and storage?

The capture and storage of carbon dioxide is a technically feasible method of making deep reductions in CO_2 emissions from sources such as those mentioned above. Although it can be implemented mainly by applying known technology developed for other purposes, its potential role in tackling climate change was not recognized as early as some other mitigation options. Indeed, the topic received little attention in IPCC's Second and Third Assessment Reports (IPCC 1996a, 2001b) – the latter contained a three-page review of technological progress, and an overview of costs and the environmental risks of applying such technology. In recent years, the technical literature on this field has expanded rapidly. Recognizing the need for a broad approach to assessing mitigation options, the potential importance of issues relating to CO_2 capture and storage and the extensive literature on other options (due to their longer history), IPCC decided to undertake a thorough assessment of CO_2 capture and storage. For these reasons it was thought appropriate to prepare a Special Report on the subject. This would constitute a source of information of comparable nature to the information available on other, more established mitigation options. In response to the invitation from the 7th Conference of the Parties to the UNFCCC in Marrakech[4], the IPCC plenary meeting in April 2002 decided to launch work on CO_2 capture and storage.

1.1.3 Preparations for this report

In preparation for this work, the 2002 Plenary decided that IPCC should arrange a Workshop under the auspices of Working Group III, with inputs from Working Groups I and II, to recommend how to proceed. This workshop took place in Regina, Canada, in November 2002 (IPCC, 2002). Three options were considered at the workshop: the production of a Technical Report, a Special Report, or the postponement of any action until the Fourth Assessment Report. After extensive discussion, the Workshop decided to advise IPCC to produce a Special Report on CO_2 capture and storage.

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1 In this report, the term 'emissions' is taken to refer to emissions from anthropogenic, rather than natural, sources.
2 CO_2 capture and storage is sometimes referred to as carbon sequestration. In this report, the term 'sequestration' is reserved for the enhancement of natural sinks of CO_2, a mitigation option which is not examined in this report but in IPCC 2000b.
3 For example, in the flue gas stream of a power plant, the other gases are mainly nitrogen and water vapour.
4 This decision called on IPCC to prepare a 'technical paper on geological carbon storage technologies'.

At IPCC's Plenary Meeting in February 2003, the Panel acknowledged the importance of issues relating to CO_2 capture and storage and decided that a Special Report would be the most appropriate way of assessing the technical, scientific and socio-economic implications of capturing anthropogenic CO_2 and storing it in natural reservoirs. The Panel duly gave approval for work to begin on such a report with 2005 as the target date for publication.

The decision of the 2002 Plenary Meeting required the report to cover the following issues:

- sources of CO_2 and technologies for capturing CO_2;
- transport of CO_2 from capture to storage;
- CO_2 storage options;
- geographical potential of the technology;
- possibility of re-using captured CO_2 in industrial applications;
- costs and energy efficiency of capturing and storing CO_2 in comparison with other large-scale mitigation options;
- implications of large-scale introduction, the environmental impact, as well as risks and risk management during capture, transport and storage;
- permanence and safety of CO_2 storage, including methods of monitoring CO_2 storage;
- barriers to the implementation of storage, and the modelling of CO_2 capture and storage in energy and climate models;
- implications for national and international emission inventories, legal aspects and technology transfer.

This report assesses information on all these topics in order to facilitate discussion of the relative merits of this option and to assist decision-making about whether and how the technology should be used.

1.1.4 Purpose of this introduction

This chapter provides an introduction in three distinct ways: it provides the background and context for the report; it provides an introduction to CCS technology; and it provides a framework for the CCS assessment methods used in later chapters.

Because this report is concerned with the physical capture, transport and storage of CO_2, the convention is adopted of using physical quantities (i.e. tonnes) of CO_2 rather than quantities of C, as is normal in the general literature on climate change. In order to make possible comparison of the results with other literature, quantities in tonnes of C are given in parenthesis.

1.2 Context for considering CO_2 Capture and Storage

1.2.1 Energy consumption and CO_2 emissions

Global consumption of energy and the associated emissions of CO_2 continued an upward trend in the early years of the 21st century (Figures 1.1, 1.2). Fossil fuels are the dominant form of energy utilized in the world (86%), and account for about 75% of current anthropogenicCO_2 emissions (IPCC, 2001c). In 2002, 149 Exajoules (EJ) of oil, 91 EJ of natural gas, and 101 EJ of coal were consumed by the world's economies (IEA, 2004). Global primary energy consumption grew at an average rate of 1.4% annually between 1990 and 1995 (1.6% per year between 1995 and 2001); the growth rates were 0.3% per year (0.9%) in the industrial sector, 2.1% per year (2.2%) in the transportation sector, 2.7% per year (2.1%) in the buildings sector, and –2.4% per year (–0.8%) in the agricultural/other sector (IEA, 2003).

Figure 1.1. World primary energy use by sector from 1971 to 2001 (IEA, 2003).

Figure 1.2. World CO_2 emissions from fossil fuel use by sector, 1971 to 2001 (IEA, 2003).

Average global CO_2 emissions[5] increased by 1.0% per year between 1990 and 1995 (1.4% between 1995 and 2001), a rate slightly below that of energy consumption in both periods. In individual sectors, there was no increase in emissions from industry between 1990 and 1995 (0.9% per year from 1995 to 2001); there was an increase of 1.7% per year (2.0%) in the transport sector, 2.3% per year (2.0%) in the buildings sector, and a fall of 2.8% per year (1.0%) in the agricultural/other sector (IEA, 2003).

Total emissions from fossil fuel consumption and flaring of natural gas were 24 $GtCO_2$ per year (6.6 GtC per year) in 2001 – industrialized countries were responsible for 47% of energy-related CO_2 emissions (not including international bunkers[6]). The Economies in transition accounted for 13% of 2001 emissions; emissions from those countries have been declining at an annual rate of 3.3% per year since 1990. Developing countries in the Asia-Pacific region emitted 25% of the global total of CO_2; the rest of the developing countries accounted for 13% of the total (IEA, 2003).

1.2.2 Sectoral CO_2 emissions

The CO_2 emissions from various sectors of the economy have been estimated by the IEA (2003). These are shown in Table 1.1, which shows that power generation is the single largest source of emissions. Other sectors where emissions arise from a few large point sources are Other Energy Industries[7] and parts of the Manufacturing and Construction sector.

Emissions from transport, which is the second largest sector (Table 1.1), have been growing faster than those from energy and industry in the last few decades (IPCC, 2001a); a key difference is that transport emissions are mainly from a multiplicity of small, distributed sources. These differences have implications for possible uses of CO_2 capture and storage, as will be seen later in this chapter.

Table 1.1. Sources of CO_2 emissions from fossil fuel combustion in 2001

1.2.3 Other greenhouse gas emissions

Anthropogenic climate change is mainly driven by emissions of CO_2 but other greenhouse gases (GHGs) also play a part[8]. Since some of the anthropogenic CO_2 comes from industrial processes and some from land use changes (mainly deforestation), the contribution from fossil fuel combustion alone is about half of the total from all GHGs.

In terms of impact on radiative forcing, methane is the next most important anthropogenic greenhouse gas after CO_2 (currently accounting for 20% of the total impact) (IPCC, 2001b). The energy sector is an important source of methane but agriculture and domestic waste disposal contribute more to the global total (IPCC, 2001c). Nitrous oxide contributes directly to climate change (currently 6% of the total impact of all GHGs); the main source is agriculture but another is

5 There are differences in published estimates of CO_2 emissions for many countries, as Marland *et al.* (1999) have shown using two ostensibly similar sources of energy statistics.

6 Emissions from international bunkers amounted to 780 Mt CO_2 (213 MtC) in 2001 (IEA, 2003).

7 The Other Energy Industries sector includes oil refineries, manufacture of solid fuels, coal mining, oil and gas extraction, and other energy-producing industries.

8 It is estimated that the global radiative forcing of anthropogenic CO_2 is approximately 60% of the total due to all anthropogenic GHGs (IPCC, 2001b).

the industrial production of some chemicals; other oxides of nitrogen have an indirect effect. A number of other gases make significant contributions (IPCC 2001c).

1.2.4 Scenarios of future emissions

Future emissions may be simulated using scenarios which are: 'alternative images of how the future might unfold and are (…) tools (…) to analyse how driving forces may influence future emissions (….) and to assess the associated uncertainties.' 'The possibility that any single emissions path will occur as described in scenarios is highly uncertain' (IPCC, 2000a). In advance of the Third Assessment Report, IPCC made an effort to identify future GHG emission pathways. Using several assumptions, IPCC built a set of scenarios of what might happen to emissions up to the year 2100. Six groups of scenarios were published (IPCC, 2000a): the 'SRES scenarios'. None of these assume any specific climate policy initiatives; in other words, they are base cases which can be used for considering the effects of mitigation options. An illustrative scenario was chosen for each of the groups. The six groups were organized into four 'families' covering a wide range of key 'future' characteristics such as demographic change, economic development, and technological change (IPCC, 2000a). Scenario families A1 and A2 emphasize economic development, whilst B1 and B2 emphasize global and local solutions for, respectively, economic, social and environmental sustainability. In addition, two scenarios, A1F1 and A1T, illustrate alternative developments in energy technology in the A1 world (see Figure TS.1 in IPCC, 2001a).

Given the major role played by fossil fuels in supplying energy to modern society, and the long periods of time involved in changing energy systems (Marchetti and Nakicenovic, 1979), the continued use of fossil fuels is arguably a good base-case scenario. Further discussion of how CCS may affect scenarios can be found in Chapter 8.

Most of these scenarios yield future emissions which are significantly higher than today's levels. In 2100, these scenarios show, on average, between 50% and 250% as much annual CO_2 emissions as current rates. Adding together all of the CO_2 emissions projected for the 21st century, the cumulative totals lie in the range of 3480 to 8050 $GtCO_2$ (950 to 2200 GtC) depending on the selected scenario (IPCC, 2001e).

It should be noted that there is potential for confusion about the term 'leakage' since this is widely used in the climate change literature in a spatial sense to refer to the displacement of emissions from one source to another. This report does not discuss leakage of this kind but it does look at the unintended release of CO_2 from storage (which may also be termed leakage). The reader is advised to be aware of the possible ambiguity in the use of the term leakage and to have regard to the context where this word is used in order to clarify the meaning.

1.3 Options for mitigating climate change

As mentioned above, the UN Framework Convention on Climate Change calls for the stabilization of the atmospheric concentration of GHGs but, at present, there is no agreement on what the specific level should be. However, it can be recognized that stabilization of concentrations will only occur once the rate of addition of GHGs to the atmosphere equals the rate at which natural systems can remove them – in other words, when the rate of anthropogenic emissions is balanced by the rate of uptake by natural processes such as atmospheric reactions, net transfer to the oceans, or uptake by the biosphere.

In general, the lower the stabilization target and the higher the level of baseline emissions, the larger the required reduction in emissions below the baseline, and the earlier that it must occur. For example, stabilization at 450 ppmv CO_2 would require emissions to be reduced earlier than stabilization at 650 ppmv, with very rapid emission reductions over the next 20 to 30 years (IPCC, 2000a); this could require the employment of all cost-effective potential mitigation options (IPCC, 2001a). Another conclusion, no less relevant than the previous one, is that the range of baseline scenarios tells us that future economic development policies may impact greenhouse gas emissions as strongly as policies and technologies especially developed to address climate change. Some have argued that climate change is more an issue of economic development, for both developed and developing countries, than it is an environmental issue (Moomaw *et al.*, 1999).

The Third Assessment Report (IPCC, 2001a) shows that, in many of the models that IPCC considered, achieving stabilization at a level of 550 ppmv would require global emissions to be reduced by 7–70% by 2100 (depending upon the stabilization profile) compared to the level of emissions in 2001. If the target were to be lower (450 ppmv), even deeper reductions (55–90%) would be required. For the purposes of this discussion, we will use the term 'deep reductions' to imply net reductions of 80% or more compared with what would otherwise be emitted by an individual power plant or industrial facility.

In any particular scenario, it may be helpful to consider the major factors influencing CO_2 emissions from the supply and use of energy using the following simple but useful identity (after Kaya, 1995):

$$CO_2 emissions = Population \times \left(\frac{GDP}{Population}\right) \times \left(\frac{Energy}{GDP}\right) \times \left(\frac{Emissions}{Energy}\right)$$

This shows that the level of CO_2 emissions can be understood to depend directly on the size of the human population, on the level of global wealth, on the energy intensity of the global economy, and on the emissions arising from the production and use of energy. At present, the population continues to rise and average energy use is also rising, whilst the amount of energy required per unit of GDP is falling in many countries, but only slowly (IPCC, 2001d). So achieving deep reductions in emissions will, all other aspects remaining constant, require major changes in the third and fourth factors in this equation, the emissions from energy technology. Meeting the challenge of the UNFCCC's goal will therefore require sharp falls in emissions from energy technology.

A wide variety of technological options have the potential to reduce net CO_2 emissions and/or CO_2 atmospheric concentrations, as will be discussed below, and there may be further options developed in the future. The targets for emission reduction will influence the extent to which each technique is used. The extent of use will also depend on factors such as cost, capacity, environmental impact, the rate at which the technology can be introduced, and social factors such as public acceptance.

1.3.1 Improve energy efficiency

Reductions in fossil fuel consumption can be achieved by improving the efficiency of energy conversion, transport and end-use, including enhancing less energy-intensive economic activities. Energy conversion efficiencies have been increased in the production of electricity, for example by improved turbines; combined heating, cooling and electric-power generation systems reduce CO_2 emissions further still. Technological improvements have achieved gains of factors of 2 to 4 in the energy consumption of vehicles, of lighting and many appliances since 1970; further improvements and wider application are expected (IPCC, 2001a). Further significant gains in both demand-side and supply-side efficiency can be achieved in the near term and will continue to slow the growth in emissions into the future; however, on their own, efficiency gains are unlikely to be sufficient, or economically feasible, to achieve deep reductions in emissions of GHGs (IPCC, 2001a).

1.3.2 Switch to less carbon-intensive fossil fuels

Switching from high-carbon to low-carbon fuels can be cost-effective today where suitable supplies of natural gas are available. A typical emission reduction is 420 kg CO_2 MWh^{-1} for the change from coal to gas in electricity generation; this is about 50% (IPCC, 1996b). If coupled with the introduction of the combined production of heat, cooling and electric power, the reduction in emissions would be even greater. This would make a substantial contribution to emissions reduction from a particular plant but is restricted to plant where supplies of lower carbon fuels are available.

1.3.3 Increased use of low- and near-zero-carbon energy sources

Deep reductions in emissions from stationary sources could be achieved by widespread switching to renewable energy or nuclear power (IPCC, 2001a). The extent to which nuclear power could be applied and the speed at which its use might be increased will be determined by that industry's ability to address concerns about cost, safety, long-term storage of nuclear wastes, proliferation and terrorism. Its role is therefore likely to be determined more by the political process and public opinion than by technical factors (IPCC, 2001a).

There is a wide variety of renewable supplies potentially available: commercial ones include wind, solar, biomass, hydro, geothermal and tidal power, depending on geographic location. Many of them could make significant contributions to electricity generation, as well as to vehicle fuelling and space heating or cooling, thereby displacing fossil fuels (IPCC, 2001a). Many of the renewable sources face constraints related to cost, intermittency of supply, land use and other environmental impacts. Between 1992 and 2002, installed wind power generation capacity grew at a rate of about 30% per year, reaching over 31 GW_e by the end of 2002 (Gipe, 2004). Solar electricity generation has increased rapidly (by about 30% per year), achieving 1.1 GW_e capacity in 2001, mainly in small-scale installations (World Energy Assessment, 2004). This has occurred because of falling costs as well as promotional policies in some countries. Liquid fuel derived from biomass has also expanded considerably and is attracting the attention of several countries, for example Brazil, due to its declining costs and co-benefits in creation of jobs for rural populations. Biomass used for electricity generation is growing at about 2.5% per annum; capacity had reached 40 GW_e in 2001. Biomass used for heat was estimated to have capacity of 210 GW_{th} in 2001. Geothermal energy used for electricity is also growing in both developed and developing countries, with capacity of 3 GW_e in 2001 (World Energy Assessment, 2004). There are therefore many options which could make deep reductions by substituting for fossil fuels, although the cost is significant for some and the potential varies from place to place (IPCC, 2001a).

1.3.4 Sequester CO_2 through the enhancement of natural, biological sinks

Natural sinks for CO_2 already play a significant role in determining the concentration of CO_2 in the atmosphere. They may be enhanced to take up carbon from the atmosphere. Examples of natural sinks that might be used for this purpose include forests and soils (IPCC, 2000b). Enhancing these sinks through agricultural and forestry practices could significantly improve their storage capacity but this may be limited by land use practice, and social or environmental factors. Carbon stored biologically already includes large quantities of emitted CO_2 but storage may not be permanent.

1.3.5 CO_2 capture and storage

As explained above, this approach involves capturing CO_2 generated by fuel combustion or released from industrial processes, and then storing it away from the atmosphere for a very long time. In the Third Assessment Report (IPCC, 2001a) this option was analyzed on the basis of a few, documented projects (e.g., the Sleipner Vest gas project in Norway, enhanced oil recovery practices in Canada and USA, and enhanced recovery of coal bed methane in New Mexico and Canada). That analysis also discussed the large potential of fossil fuel reserves and resources, as well as the large capacity for CO_2 storage in depleted oil and gas fields, deep saline formations, and in the ocean. It also pointed out that CO_2 capture and storage is more appropriate for large sources – such as central power stations, refineries, ammonia, and iron and steel plants – than for small, dispersed emission sources.

The potential contribution of this technology will be influenced by factors such as the cost relative to other options, the time that CO_2 will remain stored, the means of transport to storage sites, environmental concerns, and the acceptability of this approach. The CCS process requires additional fuel and associated CO_2 emissions compared with a similar plant without capture.

Recently it has been recognized that biomass energy used with CO_2 capture and storage (BECS) can yield net removal of CO_2 from the atmosphere because the CO_2 put into storage comes from biomass which has absorbed CO_2 from the atmosphere as it grew (Möllersten *et al.*, 2003; Azar *et al.*, 2003). The overall effect is referred to as 'negative net emissions'. BECS is a new concept that has received little analysis in technical literature and policy discussions to date.

1.3.6 Potential for reducing CO_2 emissions

It has been determined (IPCC, 2001a) that the worldwide potential for GHG emission reduction by the use of technological options such as those described above amounts to between 6950 and 9500 $MtCO_2$ per year (1900 to 2600 MtC per year) by 2010, equivalent to about 25 to 40% of global emissions respectively. The potential rises to 13,200 to 18,500 $MtCO_2$ per year (3,600 to 5,050 MtC per year) by 2020. The evidence on which these estimates are based is extensive but has several limitations: for instance, the data used comes from the 1990s and additional new technologies have since emerged. In addition, no comprehensive worldwide study of technological and economic potential has yet been performed; regional and national studies have generally had different scopes and made different assumptions about key parameters (IPCC, 2001a).

The Third Assessment Report found that the option for reducing emissions with most potential in the short term (up to 2020) was energy efficiency improvement while the near-term potential for CO_2 capture and storage was considered modest, amounting to 73 to 183 $MtCO_2$ per year (20 to 50 MtC per year) from coal and a similar amount from natural gas (see Table TS.1 in IPCC, 2001a). Nevertheless, faced with the longer-term climate challenge described above, and in view of the growing interest in this option, it has become important to analyze the potential of this technology in more depth.

As a result of the 2002 IPCC workshop on CO_2 capture and storage (IPCC, 2002), it is now recognized that the amount of CO_2 emissions which could potentially be captured and stored may be higher than the value given in Third Assessment Report. Indeed, the emissions reduction may be very significant compared with the values quoted above for the period after 2020. Wider use of this option may tend to restrict the opportunity to use other supply options. Nevertheless, such action might still lead to an increase in emissions abatement because much of the potential estimated previously (IPCC, 2001a) was from the application of measures concerned with end uses of energy. Some applications of CCS cost relatively little (for example, storage of CO_2 from gas processing as in the Sleipner project (Baklid *et al.*, 1996)) and this could allow them to be used at a relatively early date. Certain large industrial sources could present interesting low-cost opportunities for CCS, especially if combined with storage opportunities which generate compensating revenue, such as CO_2 Enhanced Oil Recovery (IEA GHG, 2002). This is discussed in Chapter 2.

1.3.7 Comparing mitigation options

A variety of factors will need to be taken into account in any comparison of mitigation options, not least who is making the comparison and for what purpose. The remainder of this chapter discusses various aspects of CCS in a context which may be relevant to decision-makers. In addition, there are broader issues, especially questions of comparison with other mitigation measures. Answering such questions will depend on many factors, including the potential of each option to deliver emission reductions, the national resources available, the accessibility of each technology for the country concerned, national commitments to reduce emissions, the availability of finance, public acceptance, likely infrastructural changes, environmental side-effects, etc. Most aspects of this kind must be considered both in relative terms (e.g., how does this compare with other mitigation options?) and absolute terms (e.g., how much does this cost?), some of which will change over time as the technology advances.

The IPCC (2001a) found that improvements in energy efficiency have the potential to reduce global CO_2 emissions by 30% below year-2000 levels using existing technologies at a cost of less than US$30/t$CO_2$ (US$100/tC). Half of this reduction could be achieved with existing technology at zero or net negative costs[9]. Wider use of renewable energy sources was also found to have substantial potential. Carbon sequestration by forests was considered a promising near-term mitigation option (IPCC, 2000b), attracting commercial attention at prices of US$0.8 to US$1.1/tCO_2 (US$3 to 4/tC). The costs quoted for mitigation in most afforestation projects are presented on a different basis from power generation options, making the afforestation examples look more favourable (Freund and Davison, 2002). Nevertheless, even after allowing for this, the cost of current projects is low.

It is important, when comparing different mitigation options, to consider not just costs but also the potential capacity for emission reduction. A convenient way of doing this is to use Marginal Abatement Cost curves (MACs) to describe the potential capacity for mitigation; these are not yet available for all mitigation options but they are being developed (see, for example, IEA GHG, 2000b). Several other aspects of the comparison of mitigation options are discussed later in this chapter and in Chapter 8.

1.4 Characteristics of CO_2 capture and storage

In order to help the reader understand how CO_2 capture and storage could be used as a mitigation option, some of the key features of the technology are briefly introduced here.

1.4.1 Overview of the CO_2 capture and storage concept and its development

Capturing CO_2 typically involves separating it from a gas stream. Suitable techniques were developed 60 years ago in connection with the production of town gas; these involved scrubbing the gas stream with a chemical solvent (Siddique, 1990). Subsequently they were adapted for related purposes, such as capturing CO_2 from the flue gas streams of coal- or gas-burning plant for the carbonation of drinks and brine, and for enhancing oil recovery. These developments required improvements to the process so as to inhibit the oxidation of the solvent in the flue gas stream. Other types of solvent and other methods of separation have been developed more recently. This technique is widely used today for separating CO_2 and other acid gases from natural gas streams[10].

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9 Meaning that the value of energy savings would exceed the technology capital and operating costs within a defined period of time using appropriate discount rates.

10 The total number of installations is not known but is probably several thousand. Kohl and Nielsen (1997) mention 334 installations using physical solvent scrubbing; this source does not provide a total for the number of chemical solvent plants but they do mention one survey which alone examined 294 amine scrubbing plants. There are also a number of membrane units and other methods of acid gas treatment in use today.

Horn and Steinberg (1982) and Hendriks *et al.* (1989) were among the first to discuss the application of this type of technology to mitigation of climate change, focusing initially on electricity generation. CO_2 removal is already used in the production of hydrogen from fossil fuels; Audus *et al.* (1996) discussed the application of capture and storage in this process as a climate protection measure.

In order to transport CO_2 to possible storage sites, it is compressed to reduce its volume; in its 'dense phase', CO_2 occupies around 0.2% of the volume of the gas at standard temperature and pressure (see Appendix 1 for further information about the properties of CO_2). Several million tonnes per year of CO_2 are transported today by pipeline (Skovholt, 1993), by ship and by road tanker.

In principle, there are many options available for the storage of CO_2. The first proposal of such a concept (Marchetti, 1977) envisaged injection of CO_2 into the ocean so that it was carried into deep water where, it was thought, it would remain for hundreds of years. In order to make a significant difference to the atmospheric loading of greenhouse gases, the amount of CO_2 that would need to be stored in this way would have to be significant compared to the amounts of CO_2 currently emitted to the atmosphere – in other words gigatonnes of CO_2 per year. The only potential storage sites with capacity for such quantities are natural reservoirs, such as geological formations (the capacity of European formations was first assessed by Holloway *et al.*, 1996) or the deep ocean (Cole *et al.*, 1993). Other storage options have also been proposed, as discussed below.

Injection of CO_2 underground would involve similar technology to that employed by the oil and gas industry for the exploration and production of hydrocarbons, and for the underground injection of waste as practised in the USA. Wells would be drilled into geological formations and CO_2 would be injected in the same way as CO_2 has been injected for enhanced oil recovery[11] since the 1970s (Blunt *et al.*, 1993; Stevens and Gale, 2000). In some cases, this could lead to the enhanced production of hydrocarbons, which would help to offset the cost. An extension of this idea involves injection into saline formations (Koide *et al.*, 1992) or into unminable coal seams (Gunter *et al.*, 1997); in the latter case, such injection may sometimes result in the displacement of methane, which could be used as a fuel. The world's first commercial-scale CO_2 storage facility, which began operation in 1996, makes use of a deep saline formation under the North Sea (Korbol and Kaddour, 1995; Baklid *et al.*, 1996).

Monitoring will be required both for purposes of managing the storage site and verifying the extent of CO_2 emissions reduction which has been achieved. Techniques such as seismic surveys, which have developed by the oil and gas industry, have been shown to be adequate for observing CO_2 underground (Gale *et al.*, 2001) and may form the basis for monitoring CO_2 stored in such reservoirs.

Many alternatives to the storage of dense phase CO_2 have been proposed: for example, using the CO_2 to make chemicals or other products (Aresta, 1987), fixing it in mineral carbonates for storage in a solid form (Seifritz, 1990; Dunsmore, 1992), storing it as solid CO_2 ('dry ice') (Seifritz, 1992), as CO_2 hydrate (Uchida *et al.*, 1995), or as solid carbon (Steinberg, 1996). Another proposal is to capture the CO_2 from flue gases using micro-algae to make a product which can be turned into a biofuel (Benemann, 1993).

[11] For example, there were 40 gas-processing plants in Canada in 2002 separating CO_2 and H_2S from produced natural gas and injecting them into geological reservoirs (see Chapter 5.2.4). There are also 76 Enhanced Oil Recovery projects where CO_2 is injected underground (Stevens and Gale, 2000).

The potential role of CO_2 capture and storage as a mitigation option has to be examined using of integrated energy system models (early studies by Yamaji (1997) have since been followed by many others). An assessment of the environmental impact of the technology through life cycle analysis was reported by Audus and Freund (1997) and other studies have since examined this further.

The concept of CO_2 capture and storage is therefore based on a combination of known technologies applied to the new purpose of mitigating climate change. The economic potential of this technique to enable deep reductions in emissions was examined by Edmonds *et al.* (2001), and is discussed in more detail in Chapter 8. The scope for further improvement of the technology and for development of new ideas is examined in later chapters, each of which focuses on a specific part of the system.

1.4.2 Systems for CO_2 capture

Figure 1.3 illustrates how CO_2 capture and storage may be configured for use in electricity generation. A conventional fossil-fuel-fired power plant is shown schematically in Figure 1.3a. Here, the fuel (e.g., natural gas) and an oxidant (typically air) are brought together in a combustion system; heat from this is used to drive a turbine/generator which produces electricity. The exhaust gases are released to atmosphere.

Figure 1.3. a) Schematic diagram of fossil-fuel-based power generation; b) Schematic diagram of post-combustion capture; c) Schematic diagram of pre-combustion capture; d) Schematic diagram of oxyfuel combustion

Figure 1.3b shows a plant of this kind modified to capture CO_2 from the flue gas stream, in other words after combustion. Once it has been captured, the CO_2 is compressed in order to transport it to the storage site. Figure 1.3c shows another variant where CO_2 is removed before combustion (pre-combustion decarbonization). Figure 1.3d represents an alternative where nitrogen is extracted from air before combustion; in other words, pure oxygen is supplied as the oxidant. This type of system is commonly referred to as oxyfuel combustion. A necessary part of this process is the recycling of CO_2 or water to moderate the combustion temperature.

1.4.3 Range of possible uses

The main application examined so far for CO_2 capture and storage has been its use in power generation. However, in other large energy-intensive industries (e.g., cement manufacture, oil refining, ammonia production, and iron and steel manufacture), individual plants can also emit large amounts of CO_2, so these industries could also use this technology. In some cases, for example in the production of ammonia or hydrogen, the nature of the exhaust gases (being concentrated in CO_2) would make separation less expensive.

The main applications foreseen for this technology are therefore in large, central facilities that produce significant quantities of CO_2. However, as indicated in Table 1.1, roughly 38% of emissions arise from dispersed sources such as buildings and, in particular, vehicles. These are generally not considered suitable for the direct application of CO_2 capture because of the economies of scale associated with the capture processes as well as the difficulties and costs of transporting small amounts of CO_2. An alternative approach would be to reduce the emissions from dispersed sources by supplying them with an energy carrier with zero net CO_2 emissions from use, such as biofuels, electricity or hydrogen (Johansson *et al.*, 1993). Electricity or hydrogen[12] from fossil fuels could be produced with CO_2 capture and this would avoid most of the CO_2 emissions at the

[12] Hydrogen is produced from fossil fuels today in oil refineries and other industrial processes.

production site (Audus *et al.*, 1996). The cost, applicability and environmental aspects of various applications are discussed later in this report.

1.4.4 Scale of the plant

Some impression of the scale of the plant involved can be gained from considering a coal-fired power plant generating 500MW_e. This would emit approximately 2.9 $MtCO_2$ per year (0.8 MtC per year) to atmosphere. A comparable plant with CO_2 capture and storage, producing a similar amount of electricity and capturing 85% of the CO_2 (after combustion) and compressing it for transportation, would emit 0.6 $MtCO_2$ per year to the atmosphere (0.16 MtC per year), in other words 80% less than in the case without capture. The latter plant would also send 3.4 $MtCO_2$ per year to storage (0.9 MtC per year). Because of its larger size, the amount of CO_2 generated by the plant with capture and compression is more than the plant without capture (in this example 38% more). This is a result of the energy requirements of the capture plant and of the CO_2 compressor. The proportion of CO_2 captured (85%) is a level readily achievable with current technology (this is discussed in Chapter 3); it is certainly feasible to capture a higher proportion and designs will vary from case to case. These figures demonstrate the scale of the operation of a CO_2 capture plant and illustrate that capturing CO_2 could achieve deep reductions in emissions from individual power plants and similar installations (IEA GHG, 2000a).

Given a plant of this scale, a pipeline of 300–400 mm diameter could handle the quantities of CO_2 over distances of hundreds of kilometres without further compression; for longer distances, extra compression might be required to maintain pressure. Larger pipelines could carry the CO_2 from several plants over longer distances at lower unit cost. Storage of CO_2, for example by injection into a geological formation, would likely involve several million tonnes of CO_2 per year but the precise amount will vary from site to site, as discussed in Chapters 5 and 6.

1.5 Assessing CCS in terms of environmental impact and cost

The purpose of this section and those that follow is to introduce some of the other issues which are potentially of interest to decision-makers when considering CCS. Answers to some of the questions posed may be found in subsequent chapters, although answers to others will depend on further work and local information. When looking at the use of CCS, important considerations will include the environmental and resource implications, as well as the cost. A systematic process of evaluation is needed which can examine all the stages of the CCS system in these respects and can be used for this and other mitigation options. A well-established method of analyzing environmental impacts in a systematic manner is the technique of Life Cycle Analysis (LCA). This is codified in the International Standard ISO 14040 (ISO, 1997). The first step required is the establishment of a system boundary, followed by a comparison of the system with CCS and a base case (reference system) without CCS. The difference will define the environmental impact of CCS. A similar approach will allow a systematic assessment of the resource and/or cost implications of CCS.

1.5.1 Establishing a system boundary

A generic system boundary is shown in Figure 1.4, along with the flows of materials into and out of the system. The key flow[13] is the product stream, which may be an energy product (such as electricity or heat), or another product with economic value such as hydrogen, cement, chemicals, fuels or other goods. In analyzing the environmental and resource implications of CCS, the convention used throughout this report is to normalize all of the system inputs and outputs to a unit quantity of product (e.g., electricity). As explained later, this concept is essential for establishing the

13 Referred to as the 'elementary flow' in life cycle analysis.

effectiveness of this option: in this particular case, the total amount of CO_2 produced is increased due to the additional equipment and operation of the CCS plant. In contrast, a simple parameter such as the amount of CO_2 captured may be misleading.

Inputs to the process include the fossil fuels used to meet process energy requirements, as well as other materials used by the process (such as water, air, chemicals, or biomass used as a feedstock or energy source). These may involve renewable or non-renewable resources. Outputs to the environment include the CO_2 stored and emitted, plus any other gaseous, liquid or solid emissions released to the atmosphere, water or land. Changes in other emissions – not just CO_2 – may also be important. Other aspects which may be relatively unique to CCS include the ability to keep the CO_2 separate from the atmosphere and the possibility of unpredictable effects (the consequences of climate change, for example) but these are not quantifiable in an LCA.

Use of this procedure would enable a robust comparison of different CCS options. In order to compare an electric power plant with CCS with other ways of reducing CO_2 emissions from electricity production (the use of renewable energy, for example), a broader system boundary may have to be considered.

Figure 1.4. System boundary for a plant or process emitting CO_2 (such as a power plant, a hydrogen production plant or other industrial process). The resource and environmental impacts of a CCS system are measured by the changes in total system input and output quantities needed to produce a unit of product.

1.5.2 Application to the assessment of environmental and resource impacts

The three main components of the CO_2 capture, transport and storage system are illustrated in Figure 1.5 as sub-systems within the overall system boundary for an electric power plant with CCS. As a result of the additional requirements for operating the CCS equipment, the quantity of fuel and other material inputs needed to produce a unit of product (e.g., one MWh of electricity) is higher than in the base case without CCS and there will also be increases in some emissions and reductions in others. Specific details of the CCS sub-systems illustrated in Figure 1.5 are presented in Chapters 3–7, along with the quantification of CCS energy requirements, resource requirements and emissions.

Figure 1.5. System components insid e the boundary of Figure 1.4 for the case of a power plant with CO_2 capture and storage. Solid arrows denote mass flows while dashed lines denote energy flows. The magnitude of each flow depends upon the type and design of each sub-system, so only some of the flows will be present or significant in any particular case. To compare a plant with CCS to another system with a similar product, for example a renewables-based power plant, a broader system boundary may have to be used.

1.5.3 Application to cost assessment

The cost of CO_2 capture and storage is typically built up from three separate components: the cost of capture (including compression), transport costs and the cost of storage (including monitoring costs and, if necessary, remediation of any release). Any income from EOR (if applicable) would help to partially offset the costs, as would credits from an emissions trading system or from avoiding a carbon tax if these were to be introduced. The costs of individual components are discussed in Chapters 3 to 7; the costs of whole systems and alternative options are considered in Chapter 8. The confidence levels of cost estimates for technologies at different stages of development and commercialization are also discussed in those chapters.

There are various ways of expressing the cost data (Freund and Davison, 2002). One convention is to express the costs in terms of US$/t$CO_2$ avoided, which has the important feature of taking into account the additional energy (and emissions) resulting from capturing the CO_2. This is very important for understanding the full effects on the particular plant of capturing CO_2, especially the increased use of energy. However, as a means of comparing mitigation options, this can be confusing since the answer depends on the base case chosen for the comparison (i.e., what is being avoided). Hence, for comparisons with other ways of supplying energy or services, the cost of systems with and without capture are best presented in terms of a unit of product such as the cost of generation (e.g., US$ MWh^{-1}) coupled with the CO_2 emissions per unit of electricity generated (e.g., tCO_2 MWh^{-1}). Users can then choose the appropriate base case best suited to their purposes. This is the approach used in this report and it is consistent with the treatment of environmental implications described above.

Expressing the cost of mitigation in terms of US$/t$CO_2$ avoided is also the approach used when considering mitigation options for a *collection* of plants (such as a national electricity system). This approach is typically found in integrated assessment modelling for policy-related purposes (see Chapter 8). The costs calculated in this way should not be compared with the cost of CO_2-avoided calculated for an *individual* power plant of a particular design as described above because the base case will not be the same. However, because the term 'avoided' is used in both cases, there can be misunderstanding if a clear distinction is not made.

1.5.4 Other cost and environmental impact issues

Most of the published studies of specific projects look at particular CO_2 sources and particular storage reservoirs. They are necessarily based on the costs for particular types of plants, so that the quantities of CO_2 involved are typically only a few million tonnes per year. Although these are realistic quantities for the first projects of this kind, they fail to reflect the potential economies of scale which are likely if or when this technology is widely used for mitigation of climate change, which would result in the capture, transport and storage of much greater quantities of CO_2. As a consequence of this greater use, reductions can be expected in costs as a result of both economies of scale and increased experience with the manufacture and operation of most stages of the CCS system. This will take place over a period of several decades. Such effects of 'learning' have been seen in many technologies, including energy technologies, although historically observed rates of improvement and cost reduction are quite variable and have not been accurately predicted for any specific technology (McDonald and Schrattenholzer, 2001).

The construction of any large plant will generate issues relating to environmental impact, which is why impact analyses are required in many countries before the approval of such projects. There will probably be a requirement for gaining a permit for the work. Chapters 3 to 7 discuss in more detail the environmental issues and impacts associated with CO_2 capture, transport and storage. At a power plant, the impact will depend largely on the type of capture system employed and the extra energy required, with the latter increasing the flows of fuel and chemical reagents and some of the emissions associated with generating a kilowatt-hour of electricity. The construction and operation of CO_2 pipelines will have a similar impact on the environment to that of the more familiar natural gas pipelines. The large-scale transportation and storage of CO_2 could also be a potential hazard, if significant amounts were to escape (see Appendix 1).

The different storage options may involve different obligations in terms of monitoring and liability. The monitoring of CO_2 flows will take place in all parts of the system for reasons of process control. It will also be necessary to monitor the systems to ensure that storage is safe and secure, to provide data for national inventories and to provide a basis for CO_2 emissions trading.

In developing monitoring strategies, especially for reasons of regulatory compliance and verification, a key question is how long the monitoring must continue; clearly, monitoring will be needed throughout the injection phase but the frequency and extent of monitoring after injection has been completed still needs to be determined, and the organization(s) responsible for monitoring in the long term will have to be identified. In addition, when CO_2 is used, for example, in enhanced oil recovery, it will be necessary to establish the net amount of CO_2 stored. The extent to which the guidelines for reporting emissions already developed by IPCC need to be adapted for this new mitigation option is discussed in Chapter 9.

In order to help understand the nature of the risks, a distinction may usefully be drawn between the slow seepage of CO_2 and potentially hazardous, larger and unintended releases caused by a rapid failure of some part of the system (see Appendix 1 for information about the dangers of CO_2 in certain circumstances). CO_2 disperses readily in turbulent air but seepage from stores under land might have noticeable effects on local ecosystems depending on the amount released and the size of the area affected. In the sea, marine currents would quickly disperse any CO_2 dissolved in seawater. CO_2 seeping from a storage reservoir may intercept shallow aquifers or surface water bodies; if these are sources of drinking water, there could be direct consequences for human activity. There is considerable uncertainty about the potential local ecosystem damage that could arise from seepage of CO_2 from underground reservoirs: small seepages may produce no detectable impact but it is known that relatively large releases from natural CO_2 reservoirs can inflict measurable damage (Sorey *et al.*, 1996). However, if the cumulative amount released from purposeful storage was significant, this could have an impact on the climate. In that case, national inventories would need to take this into account (as discussed in Chapter 9). The likely level of seepage from geological storage reservoirs is the subject of current research described in Chapter 5. Such environmental considerations form the basis for some of the legal barriers to storage of CO_2 which are discussed in Chapters 5 and 6.

The environmental impact of CCS, as with any other energy system, can be expressed as an external cost (IPCC, 2001d) but relatively little has been done to apply this approach to CCS and so it is not discussed further in this report. The results of an application of this approach to CCS can be found in Audus and Freund (1997).

1.6 Assessing CCS in terms of energy supply and CO_2 storage

Some of the first questions to be raised when the subject of CO_2 capture and storage is mentioned are:

- Are there enough fossil fuels to make this worthwhile?
- How long will the CO_2 remain in store?
- Is there sufficient storage capacity and how widely is it available?

These questions are closely related to the minimum time it is necessary to keep CO_2 out of the atmosphere in order to mitigate climate change, and therefore to a fourth, overall, question: 'How long does the CO_2 need to remain in store?' This section suggests an approach that can be used to answer these questions, ending with a discussion of broader issues relating to fossil fuels and other scenarios.

1.6.1 Fossil fuel availability

Fossil fuels are globally traded commodities that are available to all countries. Although they may be used for much of the 21st century, the balance of the different fuels may change. CO_2 capture and storage would enable countries, if they wish, to continue to include fossil fuels in their energy mix, even in the presence of severe restrictions on greenhouse gas emissions.

Whether fossil fuels will last long enough to justify the development and large-scale deployment of CO_2 capture and storage depends on a number of factors, including their depletion rate, cost, and the composition of the fossil fuel resources and reserves.

1.6.1.1 Depletion rate and cost of use

Proven coal, oil and natural gas reserves are finite, so consumption of these primary fuels can be expected to peak and then decline at some time in the future (IPCC, 2001a). However, predicting the pace at which use of fossil fuels will fall is far from simple because of the many different factors involved. Alternative sources of energy are being developed which will compete with fossil fuels, thereby extending the life of the reserves. Extracting fossil fuels from more difficult locations will increase the cost of supply, as will the use of feedstocks that require greater amounts of processing; the resultant increase in cost will also tend to reduce demand. Restrictions on emissions, whether by capping or tax, would also increase the cost of using fossil fuels, as would the introduction of CCS. At the same time, improved technology will reduce the cost of using these fuels. All but the last of these factors will have the effect of extending the life of the fossil fuel reserves, although the introduction of CCS would tend to push up demand for them.

1.6.1.2 Fossil fuel reserves and resources

In addition to the known reserves, there are significant resources that, through technological advances and the willingness of society to pay more for them, may be converted into commercial fuels in the future. Furthermore, there are thought to be large amounts of non-conventional oil (e.g., heavy oil, tars sands, shales) and gas (e.g., methane hydrates). A quantification of these in the Third Assessment Report (IPCC, 2001a) showed that fully exploiting the known oil and natural gas resources (without any emission control), plus the use of non-conventional resources, would cause atmospheric concentrations of CO_2 to rise above 750 ppmv. In addition, coal resources are even larger than those of oil and gas; consuming all of them would enable the global economy to emit 5 times as much CO_2 as has been released since 1850 (5,200 $GtCO_2$ or 1,500 GtC) (see Chapter 3 in IPCC, 2001a). A scenario for achieving significant reductions in emissions but without the use of CCS (Berk *et al.*, 2001) demonstrates the extent to which a shift away from fossil fuels would be required to stabilize at 450 ppmv by 2100. Thus, sufficient fossil fuels exist for continued use for decades to come. This means that the availability of fossil fuels does not limit the potential application of CO_2 capture and storage; CCS would provide a way of limiting the environmental impact of the continued use of fossil fuels.

1.6.2 Is there sufficient storage capacity?

To achieve stabilization at 550 ppmv, the Third Assessment Report (IPCC, 2001e) showed that, by 2100, the reduction in emissions might have to be about 38 $GtCO_2$ per year (10 GtC per year)[14] compared to scenarios with no mitigation action. If CO_2 capture and storage is to make a significant contribution towards reducing emissions, several hundreds or thousands of plants would need to be built, each capturing 1 to 5 $MtCO_2$ per year (0.27–1.4 MtC per year). These figures are consistent with the numbers of plants built and operated by electricity companies and other manufacturing enterprises.

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[14] This is an indicative value calculated by averaging the figures across the six SRES marker scenarios; this value varies considerably depending on the scenario and the parameter values used in the climate model.

Initial estimates of the capacity of known storage reservoirs (IEA GHG, 2001; IPCC, 2001a) indicate that it is comparable to the amount of CO_2 which would be produced for storage by such plants. More recent estimates are given in Chapters 5 and 6, although differences between the methods for estimating storage capacity demonstrate the uncertainties in these estimates; these issues are discussed in later chapters. Storage outside natural reservoirs, for example in artificial stores or by changing CO_2 into another form (Freund, 2001), does not generally provide similar capacity for the abatement of emissions at low cost (Audus and Oonk, 1997); Chapter 7 looks at some aspects of this.

The extent to which these reservoirs are within reasonable, cost-competitive distances from the sources of CO_2 will determine the potential for using this mitigation option.

1.6.3 How long will the CO_2 remain in storage?

This seemingly simple question is, in fact, a surprisingly complicated one to answer since the mechanisms and rates of release are quite different for different options. In this report, we use the term 'fraction retained' to indicate how much CO_2 remains in store for how long. The term is defined as follows:

- '*Fraction retained*' is the fraction of the cumulative amount of injected CO_2 that is retained in the storage reservoir over a specified period of time, for example a hundred or a million years.

Chapters 5, 6 and 7 provide more information about particular types of storage. Table AI.6 provides the relation between leakage of CO_2 and the fraction retained. The above definition makes no judgement about how the amount of CO_2 retained in storage will evolve over time – if there were to be an escape of CO_2, the rate may not be uniform.

The CO_2 storage process and its relationship to concentrations in the atmosphere can be understood by considering the stocks of stored CO_2 and the flows between reservoirs. Figure 1.6 contains a schematic diagram that shows the major stocks in natural and potential engineered storage reservoirs, and the flows to and from them. In the current pattern of fossil fuel use, CO_2 is released directly to the atmosphere from human sources. The amount of CO_2 released to the atmosphere by combustion and industrial processes can be reduced by a combination of the various mitigation measures described above. These flows are shown as alternative pathways in Figure 1.6.

Figure 1.6. Schematic diagram of stocks and flows of CO_2 with net flows of captured CO_2 to each reservoir indicated by the label CCS (these flows exclude residual emissions associated with the process of capture and storage). The release flows from each of the storage reservoirs are indicated by the labels R. The stock in the atmosphere depends upon the difference between the rates at which CO_2 reaches the atmosphere and at which it is removed. Flows to the atmosphere may be slowed by a combination of mitigation options, such as improving energy efficiency or the use of alternatives to fossil fuels, by enhancing biological storage or by utilizing CCS in geological formations, in the oceans or in chemicals or minerals.

The flows marked ***CCS*** with a subscript are the *net* tons of carbon dioxide per year that could be placed into each of the three types of storage reservoir considered in this report. Additional emissions associated with the capture and storage process are not explicitly indicated but may be considered as additional sources of CO_2 emission to the atmosphere. The potential release flows from the reservoirs to the atmosphere are indicated by ***R***, with a subscript indicating the appropriate reservoir. In some storage options, the release flows can be very small compared to the flows into those storage reservoirs.

The *amount* in storage at a particular time is determined by the capacity of the reservoir and the past history of additions to, and releases from, the reservoir. The *change* in stocks of CO_2 in a particular storage reservoir over a specified time is determined by the current stock and the relative rates at which the gas is added and released; in the case of ocean storage, the level of CO_2 in the atmosphere will also influence the net rate of release[15]. As long as the *input* storage rate exceeds the *release* rate, CO_2 will accumulate in the reservoir, and a certain amount will be stored away from the atmosphere. Analyses presented in this report conclude that the time frames for different storage options cover a wide range:

- The terrestrial biosphere stores and releases both natural and fossil fuel CO_2 through the global carbon cycle. It is difficult to provide a simple picture of the fraction retained because of the dynamic nature of this process. Typically, however, 99% is stored for decades to centuries, although the average lifetime will be towards the lower end of that range. The terrestrial biosphere at present is a net sink for carbon dioxide but some current biological sinks are becoming net sources as temperatures rise. The annual storage flows and total carbon storage capacity can be enhanced by forestry and soil management practices. Terrestrial sequestration is not explicitly considered in this report but it is covered in IPCC, 2000b.
- Oceans hold the largest amount of mobile CO_2. They absorb and release natural and fossil fuel CO_2 according to the dynamics of the global carbon cycle, and this process results in changes in ocean chemistry. The fraction retained by ocean storage at 3,000 m depth could be around 85% after 500 years. However, this process has not yet been demonstrated at a significant scale for long periods. Injection at shallower depths would result in shorter retention times. Chapter 6 discusses the storage capacity and fractions retained for ocean storage.
- In geological storage, a picture of the likely fraction retained may be gained from the observation of natural systems where CO_2 has been in natural geological reservoirs for millions of years. It may be possible to engineer storage reservoirs that have comparable performance. The fraction retained in appropriately selected and managed geological reservoirs is likely to exceed 99% over 1000 years. However, sudden gas releases from geological reservoirs could be triggered by failure of the storage seal or the injection well, earthquakes or volcanic eruptions, or if the reservoir were accidentally punctured by subsequent drilling activity. Such releases might have significant local effects. Experience with engineered natural-gas-storage facilities and natural CO_2 reservoirs may be relevant to understanding whether such releases might occur. The storage capacity and fraction retained for the various geological storage options are discussed in Chapter 5.
- Mineral carbonation through chemical reactions would provide a fraction retained of nearly 100% for exceptionally long times in carbonate rock. However, this process has not yet been demonstrated on a significant scale for long periods and the energy balance may not be favourable. This is discussed in Chapter 7.
- Converting carbon dioxide into other, possibly useful, chemicals may be limited by the energetics of such reactions, the quantities of chemicals produced and their effective lifetimes. In most cases this would result in very small net storage of CO_2. Ninety-nine per cent of the carbon will be retained in the product for periods in the order of weeks to months, depending on the product. This is discussed in Chapter 7.

1.6.4 How long does the CO_2 need to remain in storage?

In deciding whether a particular storage option meets mitigation goals, it will be important to know both the net storage capacity and the fraction retained over time. Alternative ways to frame the

[15] For further discussion of this point, see Chapter 6.

question are to ask 'How long is enough to achieve a stated policy goal?' or 'What is the benefit of isolating a specific amount of CO_2 away from the atmosphere for a hundred or a million years?' Understanding the effectiveness of storage involves the consideration of factors such as the maximum atmospheric concentration of CO_2 that is set as a policy goal, the timing of that maximum, the anticipated duration of the fossil fuel era, and available means of controlling the CO_2 concentration in the event of significant future releases.

The issue for policy is whether CO_2 will be held in a particular class of reservoirs long enough so that it will not increase the difficulty of meeting future targets for CO_2 concentration in the atmosphere. For example, if 99% of the CO_2 is stored for periods that exceed the projected time span for the use of fossil fuels, this should not to lead to concentrations higher than those specified by the policy goal.

One may assess the implications of possible future releases of CO_2 from storage using simulations similar to those developed for generating greenhouse gas stabilization trajectories[16]. A framework of this kind can treat releases from storage as delayed emissions. Some authors examined various ways of assessing unintended releases from storage and found that a delay in emissions in the order of a thousand years may be almost as effective as perfect storage (IPCC, 2001b; Herzog *et al.*, 2003; Ha-Duong and Keith, 2003)[17]. This is true if marginal carbon prices remain constant or if there is a backstop technology that can cap abatement costs in the not too distant future. However, if discount rates decline in the long term, then releases of CO_2 from storage must be lower in order to achieve the same level of effectiveness.

Other authors suggest that the climate impact of CO_2 released from imperfect storage will vary over time, so they expect carbon prices to depend on the method of accounting for the releases. Haugan and Joos (2004) found that there must be an upper limit to the rate of loss from storage in order to avoid temperatures and CO_2 concentrations over the next millennium becoming higher in scenarios with geological CCS than in those without it[18].

Dooley and Wise (2003) examined two hypothetical release scenarios using a relatively short 100-year simulation. They showed that relatively high rates of release from storage make it impossible to achieve stabilization at levels such as 450 ppmv. They imply that higher emissions trajectories are less sensitive to such releases but, as stabilization is not achieved until later under these circumstances, this result is inconclusive.

Pacala (2003) examined unintended releases using a simulation over several hundred years, assuming that storage security varies between the different reservoirs. Although this seemed to

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16 Such a framework attempts to account for the intergenerational trade-offs between climate impact and the cost of mitigation and aims to select an emissions trajectory (modified by mitigation measures) that maximizes overall welfare (Wigley *et al.*, 1996; IPCC, 2001a).

17 For example, Herzog *et al.* (2003) calculated the effectiveness of an ocean storage project relative to permanent storage using economic arguments; given a constant carbon price, the project would be 97% effective at a 3% discount rate; if the price of carbon were to increase at the same rate as the discount rate for 100 years and remain constant thereafter, the project would be 80% effective; for a similar rate of increase but over a 500 year period, effectiveness would be 45%.

18 These authors calculated the effectiveness of a storage facility measured in terms of the global warming avoided compared with perfect storage. For a store which annually releases 0.001 of the amount stored, effectiveness is around 60% after 1000 years. This rate of release would be equivalent to a fraction retained of 90% over 100 years or 60% over 500 years. It is likely that, in practice, geological and mineral storage would have lower rates of release than this (see chapters 5 and 7) and hence higher effectiveness – for example, a release rate of 0.01% per year would be equivalent to a fraction retained of 99% over 100 years or 95% over 500 years.

suggest that quite high release rates could be acceptable, the conclusion depends on extra CO_2 being captured and stored, and thereby accumulating in the more secure reservoirs. This would imply that it is important for reservoirs with low rates of release to be available.

Such perspectives omit potentially important issues such as the political and economic risk that policies will not be implemented perfectly, as well as the resulting ecological risk due to the possibility of non-zero releases which may preclude the future stabilization of CO_2 concentrations (Baer, 2003). Nevertheless, all methods imply that, if CO_2 capture and storage is to be acceptable as a mitigation measure, there must be an upper limit to the amount of unintended releases.

The discussion above provides a framework for considering the effectiveness of the retention of CO_2 in storage and suggests a potential context for considering the important policy question: 'How long is long enough?' Further discussion of these issues can be found in Chapters 8 and 9.

1.6.5 Time frame for the technology

Discussions of CCS mention various time scales. In this section, we propose some terminology as a basis for the later discussion.

Energy systems, such as power plant and electricity transmission networks, typically have operational lifetimes of 30–40 years; when refurbishment or re-powering is taken into account, the generating station can be supplying electricity for even longer still. Such lifetimes generate expectations which are reflected in the design of the plant and in the rate of return on the investment. The capture equipment could be built and refurbished on a similar cycle, as could the CO_2 transmission system. The operational lifetime of the CO_2 storage reservoir will be determined by its capacity and the time frame over which it can retain CO_2, which cannot be so easily generalized. However, it is likely that the phase of filling the reservoir will be at least as long as the operational lifetime of a power plant[19]. In terms of protecting the climate, we shall refer to this as the **medium term**, in contrast to the **short-term** nature of measures connected with decisions about operating and maintaining such facilities.

By contrast, the mitigation of climate change is determined by longer time scales: for example, the lifetime (or adjustment time) of CO_2 in the atmosphere is often said to be about 100 years (IPCC, 2001c). Expectations about the mitigation of climate change typically assume that action will be needed during many decades or centuries (see, for example, IPCC, 2000a). This will be referred to as the **long term**.

Figure 1.7. The response of atmospheric CO_2 concentrations due to emissions to the atmosphere. Typical values for 'short term', 'medium term', 'long term' and' very long term' are years, decades, centuries, millennia, respectively. In this example, cumulative emissions are limited to a maximum value and concentrations stabilize at 550 ppmv (adapted from Kheshgi, 2003). This figure is indicative and should not be read as prescribing specific values for any of these periods. If the goal were to constrain concentrations in the atmosphere to lower levels, such as 450 ppmv, greater reductions in emission rates would be required.

Even so, these descriptors are inadequate to describe the storage of CO_2 as a mitigation measure. As discussed above, it is anticipated that CO_2 levels in the atmosphere would rise, peak and decline over a period of several hundred years in virtually all scenarios; this is shown in Figure 1.7. If there

[19] It should be noted that there will not necessarily be a one-to-one correspondence between a CO_2-producing plant and storage reservoir. Given a suitable network for the transport of CO_2, the captured CO_2 from one plant could be stored in different locations during the lifetime of the producing plant.

is effective action to mitigate climate change, the peak would occur sooner (and be at a lower level) than if no action is taken. As suggested above, most of the CO_2 must be stored for much longer than the time required to achieve stabilization. We consider this to be the **very long term**, in other words periods of time lasting centuries or millennia. Precisely how long is a subject of much debate at present and this will be explored in later chapters.

1.6.6 Other effects of introducing CCS into scenarios

In view of the economic importance of energy carriers (more than 2 trillion dollars annually, World Energy Assessment, 2004) as well as fossil fuel's contribution to climate forcing (50 to 60% of the total), the decision to invest economic resources in the development of a technology such as CCS may have far-reaching consequences, including implications for equity and sustainable development (these are discussed in the following section). This emphasizes the importance of considering the wider ramifications of such investment.

The implementation of CCS would contribute to the preservation of much of the energy infrastructure established in the last century and may help restrain the cost of meeting the target for emissions reduction. From another perspective, its use may reduce the potential for application of alternative energy sources (Edmonds *et al.*, 2001). As noted in section 1.3, the mitigation of climate change is a complex issue and it seems likely that any eventual solution will involve a portfolio of methods[20]. Even so, there is concern in some quarters that the CO_2 capture and storage option could capture financial resources and the attention of policymakers that would otherwise be spent on alternative measures, even though this issue has not been extensively analyzed in the literature.

The possibility of obtaining net negative emissions when coupling biomass energy and CCS may provide an opportunity to reduce CO_2 concentration in the atmosphere if this option is available at a sufficiently large scale. In view of the uncertainty about the safe concentration of CO_2 in the atmosphere, a large-scale option providing net negative emissions could be especially useful in the light of the precautionary principle.

1.6.6.1 Effect of CCS on energy supply and use

All of the SRES scenarios (IPCC, 2000a) show significant consumption of fossil fuels for a long time into the future. One of the consequences of deploying CCS would be a continued use of fossil fuels in the energy mix but the minimization of their effect on the climate system and environment. By enabling countries to access a wider range of energy supplies than would otherwise be the case, energy security will be improved. Such aspects are important when considering climate change policy and sustainable development: as indicated before, decision-makers are likely to balance pure economic effectiveness against other socially relevant issues.

The successful development and implementation of CCS on a large scale might therefore be interpreted by society as a driver for reinforcing socio-economic and behavioural trends that are increasing total energy use, especially in developed countries and within high-income groups in developing countries[21] (IPCC, 2001a).

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[20] The optimum portfolio of mitigation measures is likely to be different in different places and at different times. Given the variety of measures available, it seems likely that several will be used in a complementary fashion as part of the portfolio, and that there will not be a single clear 'winner' amongst them.

[21] For example, housing units in many countries are increasing in size, and the intensity of electrical appliance use is increasing. The use of electrical office equipment in commercial buildings is also rising rapidly.

1.6.6.2 Effect of CCS on technological diversity

The fossil fuel energy system and its infrastructure can be thought of as a technology cluster. Such a phenomenon can be recognized as possibly presenting dangers as well as offering benefits for society. It can lead to specialization as innovations improve on dominant technologies, thereby generating further innovations which help to retain market share. On the other hand, innovations in technologies with small market shares are less valuable and so there is less incentive to improve on those technologies; a minor technology can therefore become trapped by high costs and a small market share. This phenomenon leads to path dependence or technology lock-in (Bulter and Hofkes, 2004; Unruh, 2000). Although CCS has not yet been examined specifically in this respect, it may be that reinforcing the position of the fossil fuel energy system may present barriers to increased technological diversity (a key element in evolutionary change; see Nelson and Winter, 1982).

It could be argued that increasing demand for some alternative energy sources will bring significant additional benefits outside the climate change arena such as rural sector jobs, or a large labour force for maintenance (World Energy Assessment, 2004). It is not possible to forecast the full societal impacts of such technology in its early days, especially as it seems likely that stabilizing atmospheric concentrations of CO_2 will require the full slate of available technologies (including ones not yet developed). The available information is not adequate for predictions of the differences in job creation potential between different mitigation options.

In view of the paucity of literature on these aspects of CCS, this report cannot provide tools for a full quantitative judgment of options; it merely flags some of the other issues that decision-makers will wish to consider. This is further discussed in Chapter 8.

1.6.6.3 Financing of the projects

Compared to a similar plant that releases CO_2 to the atmosphere, a facility with capture and storage will cost more to build and to operate and will be less efficient in its use of primary energy. If regulations are adopted which cause the owners of CO_2-emitting plant to limit emissions, and they choose to use CCS (or any other measure which increases their costs), they will need to find ways to recover the extra costs or accept a lower rate of return on their investment. In circumstances where emissions trading is allowed, companies may, in some cases, reduce the cost of meeting emission targets by buying or selling credits. Where the project is located in another Annex I country, it may be possible to fund this through Joint Implementation (JI). The Clean Development Mechanism (CDM) may provide opportunities for developing countries to acquire technology for emission reduction purposes, with some of the costs being borne by external funders who can claim credit for these investments. At the time of writing, it is uncertain whether CCS projects would be covered by the CDM and there are many issues to be considered. The current low value of Certified Emission Reductions is a major barrier to such projects at present (IEA GHG, 2004a). It is possible that some CO_2-EOR projects could be more attractive, especially if the project would also delay the abandonment of a field or prevent job losses. The issue of the longevity of storage has still to be resolved but the longer retention time for geological formations may make it easier for CCS to be accepted than was the case for natural sinks. A number of countries have the potential to host CCS projects involving geological storage under CDM (IEA GHG, 2004a) but the true potential can only be assessed when the underground storage resources have been mapped. The above discussion shows that there are many questions to be answered about the financing of such options, not least if proposed as a project under the flexible mechanisms of the Kyoto Protocol.

1.6.7 Societal requirements

Even if CO_2 capture and storage is cost-effective and can be recognized as potentially fulfilling a useful role in energy supply for a climate-constrained world, there will be other aspects that must be addressed before it can be widely used. For example, what are the legal issues that face this technology? What framework needs to be put in place for long-term regulation? Will CO_2 capture and storage gain public acceptance?

1.6.7.1 Legal issues concerning CCS

Some legal questions about CCS can be identified and answered relatively easily; for example, the legal issues relating to the process of capturing CO_2 seem likely to be similar to those facing any large chemical plant. Transporting CO_2 through pipelines can probably be managed under current regulatory regimes for domestic and international pipelines. The extent to which the CO_2 is contaminated with other substances, such as compounds of sulphur (see Chapter 4), might alter its classification to that of a hazardous substance, subjecting it to more restrictive regulation. However, the storage of carbon dioxide is likely to pose new legal challenges. What licensing procedure will be required by national authorities for storage in underground reservoirs onshore? It seems likely that factors to be considered will include containment criteria, geological stability, potential hazard, the possibility of interference with other underground or surface activities and agreement on sub-surface property rights, and controls on drilling or mining nearby.

Storage in geological formations below the sea floor will be controlled by different rules from storage under land. The Law of the Sea[22], the London Convention and regional agreements such as the OSPAR Convention[23] will affect storage of CO_2 under the sea but the precise implications have yet to be worked out. This is discussed further in Chapter 5. Ocean storage raises a similar set of questions about the Law of the Sea and the London Convention but the different nature of the activity may generate different responses. These are discussed in Chapter 6.

A further class of legal issues concerns the responsibility for stored carbon dioxide. This is relevant because the CO_2 will have been the subject of a contract for storage, or a contract for emissions reduction, and/or because of the possibility of unintended release. Should society expect private companies to be responsible over centuries for the storage of CO_2? A judgement may have to be made about a reasonable balance between the costs and benefits to current and to future generations. In the case of the very long-term storage of nuclear waste, governments have taken on the responsibility for managing storage; the companies that generate the waste, and make a profit from using the nuclear material, pay a fee to the government to take responsibility. In other fields, the deep-well injection of hazardous materials is sometimes the responsibility of governments and sometimes the responsibility of the companies concerned under a licensing system (IEA GHG, 2004b). Rules about insurance and about liability (if there were to be a release of CO_2) will need to be developed so that, even if something happens in the distant future, when the company that stored it is no longer in business, there will be a means of ensuring another organization is capable and willing to accept responsibility.

The information on legal issues presented in this report reflects the best understanding at the time of writing but should not be taken as definitive as the issues have not been tested.

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[22] The full text of these conventions is accessible on the Internet.

[23] Issues of interest for this report are at the time of writing being discussed in the OSPAR convention that regulates the uses of the North East Atlantic.

1.6.7.2 Public acceptance

Only a few studies have been carried out of public attitudes towards CCS. Such research presents challenges because the public is not familiar with the technology, and may only have a limited understanding of climate change and the possibilities for mitigation. As a result the studies completed to date have had to provide information on CCS (and on climate change) to their subjects. This tends to limit the scale of the study which can be carried out. This issue is examined in more detail in Chapter 5.

What form of public consultation will be needed before approval of a CCS project? Will the public compare CCS with other activities below ground such as the underground storage of natural gas or will CCS be compared to nuclear waste disposal? Will they have different concerns about different forms of storage, such as geological or ocean storage of CO_2? Will the general attitude towards building pipelines affect the development of CO_2 pipelines? These and other issues are the subject of current discussion and investigation.

When a CCS project is proposed, the public and governments will want to be satisfied that storage of carbon dioxide is so secure that emissions will be reduced and also that there will be no significant threat to human health or to ecosystems (Hawkins, 2003). Carbon dioxide transport and storage will have to be monitored to ensure there is little or no release to the atmosphere but monitoring issues are still being debated. For example, can the anticipated low rates of CO_2 release from geological storage be detected by currently available monitoring techniques? Who will do this monitoring (IEA GHG, 2004b)? How long should monitoring continue after injection: for periods of decades or centuries (IEA GHG, 2004c)?

1.7 Implications for technology transfer and sustainable development

1.7.1 Equity and sustainable development

The climate change issue involves complex interactions between climatic, environmental, economic, political, institutional, social, scientific, and technological processes. It cannot be addressed in isolation from broader societal goals, such as equity or sustainable development (IPCC, 2001a), or other existing or probable future sources of environmental, economic or social stress. In keeping with this complexity, a multiplicity of approaches has emerged to analyze climate change and related challenges. Many of these incorporate concerns about development, equity, and sustainability, albeit partially and gradually (IPCC, 2001a).

Sustainable development is too complex a subject for a simple summary; the study of this field aims to assess the benefits and trade-offs involved in the pursuit of the multiple goals of environmental conservation, social equity, economic growth, and eradication of poverty (IPCC 2001a, Chapter 1). Most of the studies only make a first attempt to integrate a number of important sustainable development indicators and only a few have considered the implications for CCS (Turkenburg, 1997). To date, studies have focused on short-term side-effects of climate change mitigation policies (e.g., impact on local air and water quality) but they have also suggested a number of additional indicators to reflect development (e.g., job creation) and social impact (e.g., income distribution). CCS also poses issues relating to long-term liability for possible unintended releases or contamination which may have inter-generational and, in some cases, international consequences[24]. Further studies will be needed to develop suitable answers about CCS. In particular, long-term liability must be shown to be compatible with sustainable development.

[24] Some legislation is already in place which will influence this: for example both the London Convention (Article X) and its 1996 Protocol (Article 15) contain provisions stating that liability is in accordance with the principles of

There are various viewpoints relating to climate policy: one is based on cost-effectiveness, another on environmental sustainability, and another on equity (Munasinghe and Swart, 2005). Most policies designed to achieve the mitigation of climate change also have other important rationales. They can be related to the objectives of development, sustainability and equity. 'Conventional' climate policy analyses have tended to be driven (directly or indirectly) by the question: what is the cost-effective means of mitigating climate change for the global economy? Typically, these analyses start from a baseline projection of greenhouse gas emissions and reflect a specific set of socio-economic projections. Equity considerations are added to the process, to broaden the discussion from global welfare as a single subject to include the effects of climate change and mitigation policies on existing inequalities, amongst and within nations. The goal here goes beyond providing for basic survival, extending to a standard of living that provides security and dignity for all.

Ancillary effects of mitigation policies may include reductions in local and regional air pollution, as well as indirect effects on transportation, agriculture, land use practices, biodiversity preservation, employment, fuel security, etc. (Krupnick *et al.*, 2000). The concept of 'co-benefits' can be used to capture dimensions of the response to mitigation policies from the equity and sustainability perspectives in a way that could modify the projections produced by those working from the cost-effectiveness perspective. As yet, little analysis has been reported of the option of CCS in these respects.

Will CO_2 capture and storage favour the creation of job opportunities for particular countries? Will it favour technological and financial elitism or will it enhance equity by reducing the cost of energy? In terms of sustainable development, does the maintenance of the current market structures aid those countries that traditionally market fossil fuels, relative to those that import them? Is this something which mitigation policies should be developed to assist? There are no simple answers to these questions but policymakers may want to consider them. However, no analysis of these aspects of CCS is yet available. Furthermore, the mitigation options available will vary from country to country; in each case, policymakers have to balance such ancillary benefits with the direct benefits of the various options in order to select the most appropriate strategy.

1.7.2 Technology transfer

Article 4.5 of the UNFCCC requires all Annex I countries to take 'All practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other parties, particularly developing countries, to enable them to implement provisions of the convention.' This applies to CCS as much as it does to any other mitigation option. This was precisely stated in the declaration issued at COP 7 (UNFCCC, 2001). Paragraph 8, item (d) states:

'Cooperating in the development, diffusion and transfer (…) and/or technologies relating to fossil fuels that capture and store GHGs, and encouraging their wider use, and facilitating the participation of the least developed countries and other Parties not included in Annex I in this effort'

In achieving these objectives of the Convention, several key elements will have to be considered (IPCC, 2001a). These are discussed in the IPCC Special Report on Technology Transfer (IPCC,

international law regarding a state's responsibility for damage caused to the environment of other states or to any other area of the environment. Similarly, regional agreements such as the OSPAR Convention incorporate the 'polluter pays' principle (Article 2(b)).

2000c), which looked into all aspects of the processes affecting the development, application and diffusion of technology. This looks at technology transfer for the purposes of adapting to climate change as well as for mitigation. It looks at processes within countries and between countries, covering hardware, knowledge and practices. Particularly important are the assessment of technology needs, the provision of technology information, capacity building, the creation of an enabling environment, and innovative financing to facilitate technology transfer.

Although no academic examination of CCS in these respects has yet been undertaken, some remarks can be made in general about this mitigation option.

1.7.2.1 Potential barriers

Technology transfer faces several barriers, including intellectual property rights, access to capital, etc. As with any new technology, CCS opens opportunities for proprietary rights. As it will rely on the development and/or integration of technologies, some of which are not yet used for such purposes, there is considerable scope for learning by doing. Several developing countries are already taking an active interest in this option, where they have national resources that would allow them to make use of this technique. For example, Deshun *et al.* (1998) have been looking at the related technique of CO_2-EOR. Some of the key technologies will be developed by particular companies (as is occurring with wind power and solar photovoltaics) but will the intellectual property for CCS be accumulated in the hands of a few? CCS will involve both existing and future technologies, some of which will be proprietary. Will the owners of these rights to be willing to exploit their developments by licensing others to use them? At present it appears to be too early to answer these questions.

Given that the essential parts of CCS systems are based on established technology, it can be expected that it will be accessible to anyone who can afford it and wants to buy it. Several companies currently offer competing methods of capturing CO_2; pipelines for CO_2 and ships are constructed today by companies specializing in this type of equipment; the drilling of injection wells is standard practice in the oil and gas industry, and is carried out by many companies around the world. More specialist skills may be required to survey geological reservoirs; indeed, monitoring of CO_2 underground is a very new application of seismic analysis. However, it is anticipated that, within a short space of time, these will become as widely available as other techniques derived from the international oil and gas industry. Making these technologies available to developing countries will pose similar challenges as those encountered with other modern technological developments. This shows the relevance of the UNFCCC declaration on technology transfer quoted above to ensure that developing countries have access to the option of CO_2 capture and storage.

1.7.2.2 Potential users

CO_2 emissions are rising rapidly in some developing countries; if these countries wish to reduce the rate of increase of emissions, they will want to have access to a range of mitigation options, one of which could be CCS. Initially it seems likely that CCS would be exploited by countries with relevant experience, such as oil and gas production[25], but this may not be the case in other natural resource sectors. Will there be fewer opportunities for the transfer of CCS technology than for other mitigation options where technologies are in the hands of numerous companies? Or will the

[25] In 1999, there were 20 developing countries that were each producing more than 1% of global oil production, 14 developing countries that were each producing more than 1% of global gas production, and 7 developing countries producing more than 1% of global coal production (BP, 2003).

knowledge and experience already available in the energy sector in certain developing countries provide an opportunity for them to exploit CCS technologies? Will CO_2 capture and storage technologies attract more interest from certain developing countries if applied to biomass sources[26]? If there is a year-round supply of CO_2 from the biomass processing plant and good storage reservoirs within reasonable distance, this could be an important opportunity for technology transfer. As yet there are no answers to these questions.

1.8 Contents of this report

This report provides an assessment of CO_2 capture and storage as an option for the mitigation of climate change. The report does not cover the use of natural sinks to sequester carbon since this issue is covered in the Land Use, Land Use Change and Forestry report (IPCC, 2000b) and in IPCC's Third Assessment Report (IPCC, 2001a).

There are many technical approaches which could be used for capturing CO_2. They are examined in Chapter 3, with the exception of biological processes for fixation of CO_2 from flue gases, which are not covered in this report. The main natural reservoirs which could, in principle, hold CO_2 are geological formations and the deep ocean; they are discussed in Chapters 5 and 6 respectively. Other options for the storage and re-use of CO_2 are examined in Chapter 7.

Chapter 2 considers the geographical correspondence of CO_2 sources and potential storage reservoirs, a factor that will determine the cost-effectiveness of moving CO_2 from the place where it is captured to the storage site. A separate chapter, Chapter 4, is dedicated to transporting CO_2 from capture to storage sites.

The overall cost of this technology and the consequences of including it in energy systems models are described in Chapter 8. Some of the other requirements outlined above, such as legality, applicable standards, regulation and public acceptance, are discussed in detail at the appropriate point in several of the chapters. Governments might also wish to know how this method of emission reduction would be taken into account in national inventories of greenhouse gas emissions. This area is discussed in Chapter 9. Government and industry alike will be interested in the accessibility of the technology, in methods of financing the plant and in whether assistance will be available from industry, government or supra-national bodies. At present, it is too early in the exploitation of this technology to make confident predictions about these matters. Two appendices provide information about the properties of CO_2 and carbon-containing fuels, and a glossary of terms. Gaps and areas for further work are discussed in the chapters and in the Technical Summary to this report.

[26] For further discussion of using CCS with biomass, see Chapter 2.

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Tables

Table 1.1. Sources of CO_2 emissions from fossil fuel combustion in 2001

	Emissions	
	($MtCO_2\ yr^{-1}$)	**($MtC\ yr^{-1}$)**
Public Electricity and Heat Production	8,236	2,250
Autoproducers	963	263
Other Energy Industries	1,228	336
Manufacturing & Construction	4,294	1,173
Transport	5,656	1,545
of which: Road	4,208	1,150
Other Sectors	3,307	903
of which: Residential	1,902	520
TOTAL	23,684	6,470

Source: IEA, 2003.

Figures

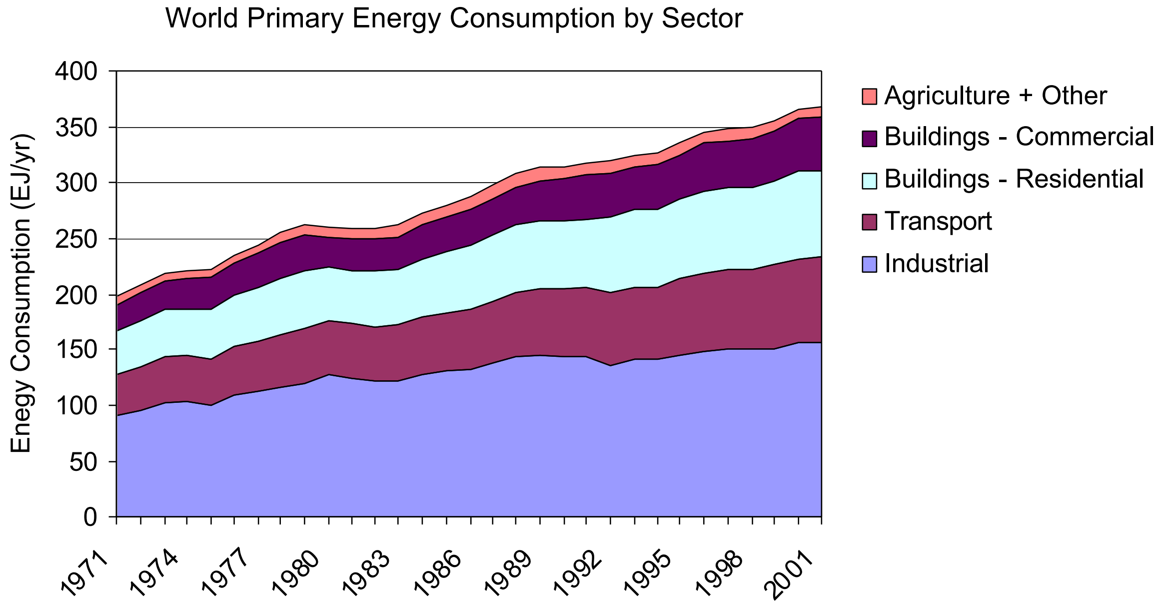

Figure 1.1. World primary energy use by sector fro m 1971 to 2001 (IEA, 2003).

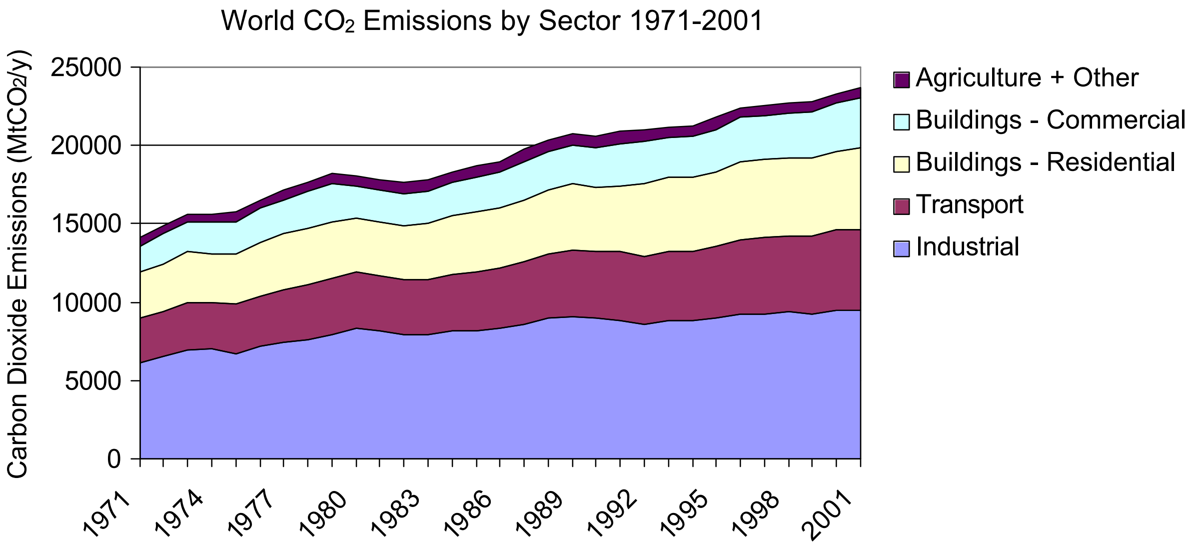

Figure 1.2. World CO_2 emissions from fossil fuel use by sector, 1971 to 2001 (IEA, 2003).

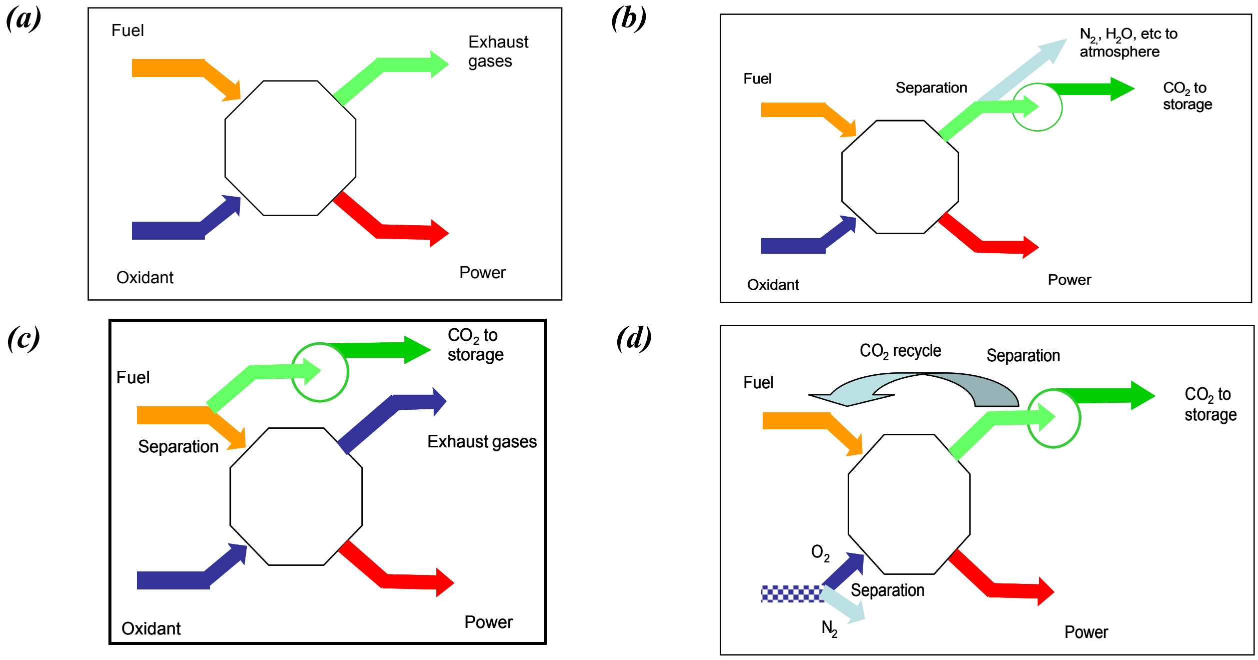

Figure 1.3. a) Schematic diagram of fossil-fuel-based power generation; b) Schematic diagram of post-combustion capture; c) Schematic diagram of pre-combustion capture; d) Schematic diagram of oxyfuel combustion

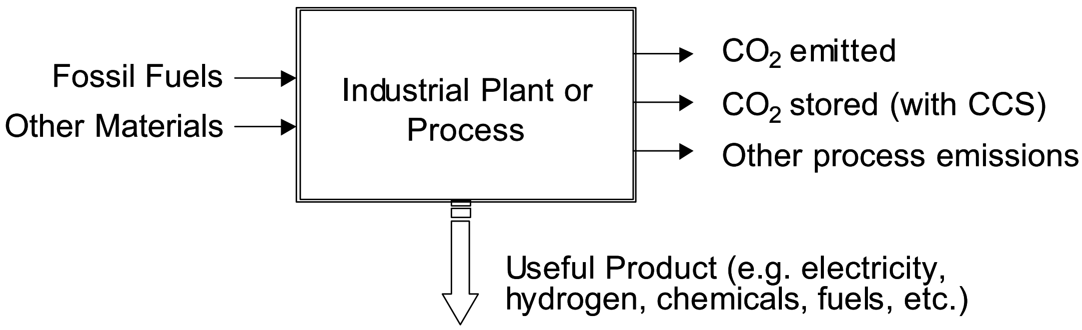

Figure 1.4. System boundary for a plant or process emitting CO_2 (such as a power plant, a hydrogen production plant or other industrial process). The resource and environmental impacts of a CCS system are measured by the changes in total system input and output quantities needed to produce a unit of product.

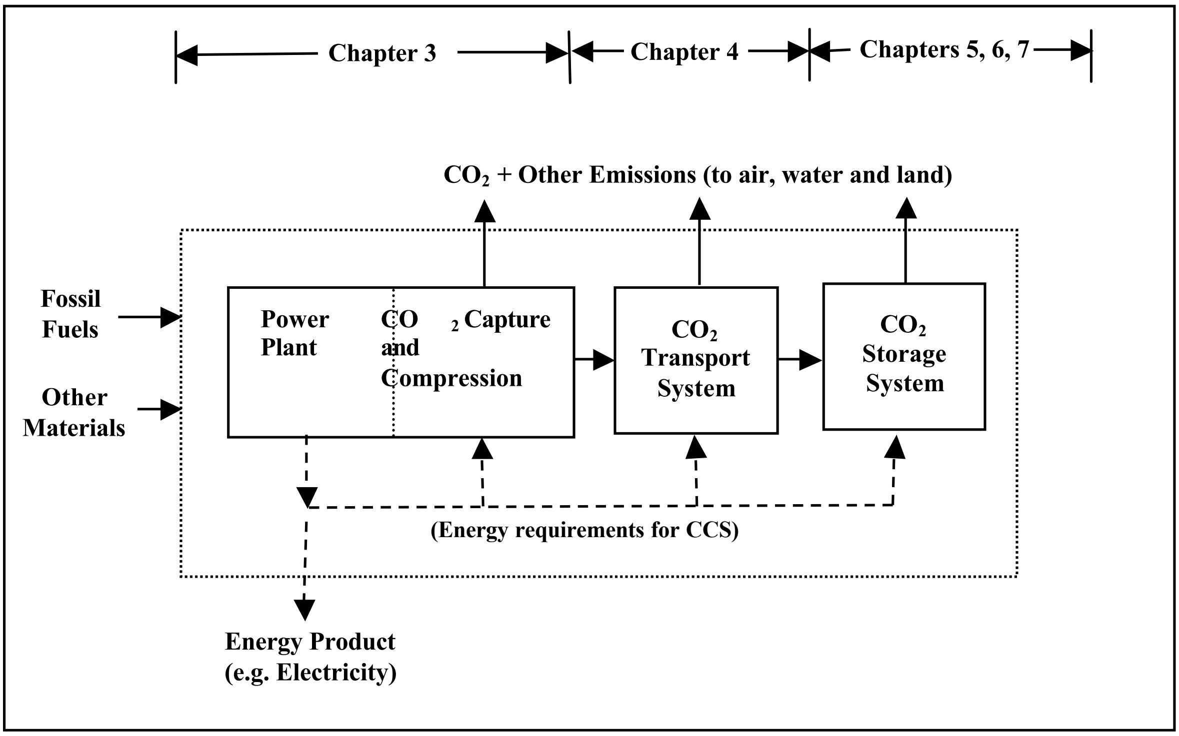

Figure 1.5. System com ponents inside the boundary of Figure 1.4 for the case of a power plant with CO_2 capture and storage. Solid arrows denote mass flows while dashed lines denote energy flows. The magnitude of each flow depends upon the type and design of each sub-system, so only some of the flows will be present or significant in any particular case. To compare a plant with CCS to another system with a similar product, for example a renewables-based power plant, a broader system boundary may have to be used.

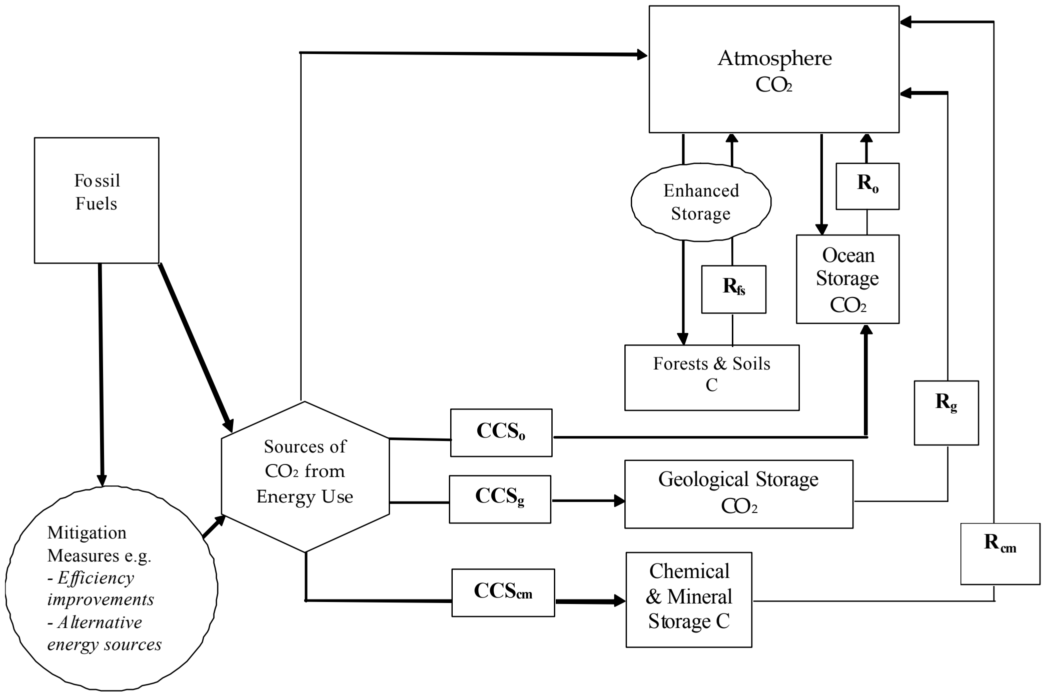

Figure 1.6. Schematic diagram of stocks and flows of CO_2 with net flows of captured CO_2 to each reservoir indicated by the label CCS (these flows exclude residual emissions associated with the process of capture and storage). The release flows from each of the storage reservoirs are indicated by the labels R. The stock in the atmosphere depends upon the difference between the rates at which CO_2 reaches the atmosphere and at which it is removed. Flows to the atmosphere may be slowed by a combination of mitigation options, such as improving energy efficiency or the use of alternatives to fossil fuels, by enhancing biological storage or by utilizing CCS in geological formations, in the oceans or in chemicals or minerals.

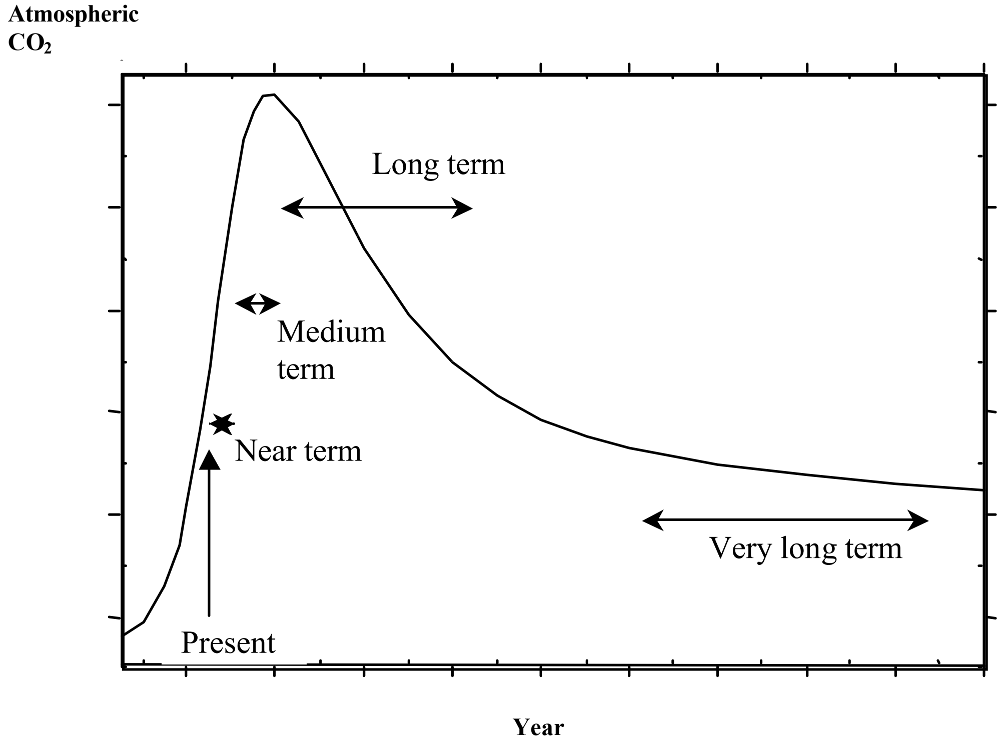

Figure 1.7. The response of atmospheric CO_2 concentrations due to emissions to the atmosphere. Typical values for 'short term', 'medium term', 'long term' and' very long term' are years, decades, centuries, millennia, respectively. In this example, cumulative emissions are limited to a maximum value and concentrations stabilize at 550 ppmv (adapted from Kheshgi, 2003). This figure is indicative and should not be read as prescribing specific values for any of these periods. If the goal were to constrain concentrations in the atmosphere to lower levels, such as 450 ppmv, greater reductions in emission rates would be required.