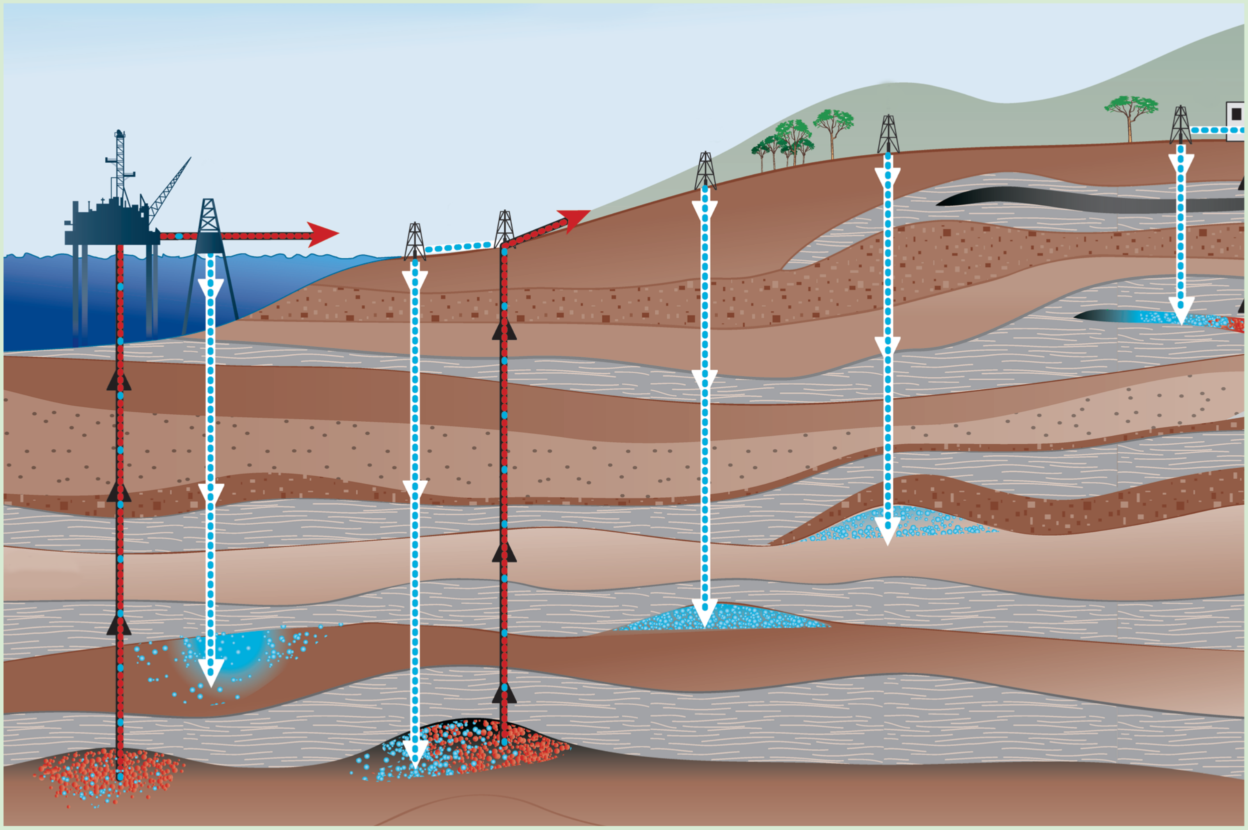
CARBON DIOXIDE CAPTURE AND STORAGE



WMO

Intergovernmental Panel on Climate Change

UNEP

CARBON DIOXIDE CAPTURE AND STORAGE

This Intergovernmental Panel on Climate Change (IPCC) Special Report provides information for policymakers, scientists and engineers in the field of climate change and reduction of CO_2 emissions. It describes sources, capture, transport, and storage of CO_2. It also discusses the costs, economic potential, and societal issues of the technology, including public perception and regulatory aspects. Storage options evaluated include geological storage, ocean storage, and mineral carbonation. Notably, the report places CO_2 capture and storage in the context of other climate change mitigation options, such as fuel switch, energy efficiency, renewables and nuclear energy.

This report shows that the potential of CO_2 capture and storage is considerable, and the costs for mitigating climate change can be decreased compared to strategies where only other climate change mitigation options are considered. The importance of future capture and storage of CO_2 for mitigating climate change will depend on a number of factors, including financial incentives provided for deployment, and whether the risks of storage can be successfully managed. The volume includes a *Summary for Policymakers* approved by governments represented in the IPCC, and a *Technical Summary.*

The IPCC Special Report on *Carbon Dioxide Capture and Storage* provides invaluable information for researchers in environmental science, geology, engineering and the oil and gas sector, policymakers in governments and environmental organizations, and scientists and engineers in industry.

IPCC Special Report on

Carbon Dioxide Capture and Storage

Edited by

Bert Metz **Ogunlade Davidson** **Heleen de Coninck**

Manuela Loos **Leo Meyer**

Prepared by Working Group III of the
Intergovernmental Panel on Climate Change

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Cover image: Schematic of geological storage options (Courtesy CO2CRC).

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Annexes

Foreword

The Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988. Its terms of reference include: (i) to assess available scientific and socio-economic information on climate change and its impacts and on the options for mitigating climate change and adapting to it and (ii) to provide, on request, scientific/technical/socio-economic advice to the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC). From 1990, the IPCC has produced a series of Assessment Reports, Special Reports, Technical Papers, methodologies and other products that have become standard works of reference, widely used by policymakers, scientists and other experts.

At COP7, a draft decision was taken to invite the IPCC to write a technical paper on geological storage of carbon dioxide[a]. In response to that, at its 20th Session in 2003 in Paris, France, the IPCC agreed on the development of the Special Report on Carbon dioxide Capture and Storage.

This volume, the Special Report on Carbon dioxide Capture and Storage, has been produced by Working Group III of the IPCC and focuses on carbon dioxide capture and storage (CCS) as an option for mitigation of climate change. It consists of 9 chapters covering sources of CO_2, the technical specifics of capturing, transporting and storing it in geological formations, the ocean, or minerals, or utilizing it in industrial processes. It also assesses the costs and potential of CCS, the environmental impacts, risks and safety, its implications for greenhouse gas inventories and accounting, public perception, and legal issues.

As is usual in the IPCC, success in producing this report has depended first and foremost on the knowledge, enthusiasm and cooperation of many hundreds of experts worldwide, in many related but different disciplines. We would like to express our gratitude to all the Coordinating Lead Authors, Lead Authors, Contributing Authors, Review Editors and Expert Reviewers. These individuals have devoted enormous time and effort to produce this report and we are extremely grateful for their commitment to the IPCC process. We would like to thank the staff of the Working Group III Technical Support Unit and the IPCC Secretariat for their dedication in coordinating the production of another successful IPCC report. We are also grateful to the governments, who have supported their scientists' participation in the IPCC process and who have contributed to the IPCC Trust Fund to provide for the essential participation of experts from developing countries and countries with economies in transition. We would like to express our appreciation to the governments of Norway, Australia, Brazil and Spain, who hosted drafting sessions in their countries, and especially the government of Canada, that hosted a workshop on this subject as well as the 8th session of Working Group III for official consideration and acceptance of the report in Montreal, and to the government of The Netherlands, who funds the Working Group III Technical Support Unit.

We would particularly like to thank Dr. Rajendra Pachauri, Chairman of the IPCC, for his direction and guidance of the IPCC, Dr. Renate Christ, the Secretary of the IPCC and her staff for the support provided, and Professor Ogunlade Davidson and Dr. Bert Metz, the Co-Chairmen of Working Group III, for their leadership of Working Group III through the production of this report.

Michel Jarraud
Secretary-General,
World Meteorological Organization

Klaus Töpfer
Executive Director,
United Nations Environment Programme and
Director-General,
United Nations Office in Nairobi

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[a] See http://unfccc.int, Report of COP7, document FCCC/CP/2001/13/Add.1, Decision 9/CP.7 (Art. 3.14 of the Kyoto Protocol), Draft decision -/CMP.1, para 7, page 50: "*Invites* the Intergovernmental Panel on Climate Change, in cooperation with other relevant organisations, to prepare a technical paper on geological carbon storage technologies, covering current information, and report on it for the consideration of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol at its second session".

Preface

This Special Report on Carbon dioxide Capture and Storage (SRCCS) has been prepared under the auspices of Working Group III (Mitigation of Climate Change) of the Intergovernmental Panel on Climate Change (IPCC). The report has been developed in response to an invitation of the United Nations Framework Convention on Climate Change (UNFCCC) at its seventh Conference of Parties (COP7) in 2001. In April 2002, at its 19th Session in Geneva, the IPCC decided to hold a workshop, which took place in November 2002 in Regina, Canada. The results of this workshop were a first assessment of literature on CO_2 capture and storage, and a proposal for a Special Report. At its 20th Session in 2003 in Paris, France, the IPCC endorsed this proposal and agreed on the outline and timetable[b]. Working Group III was charged to assess the scientific, technical, environmental, economic, and social aspects of capture and storage of CO_2. The mandate of the report therefore included the assessment of the technological maturity, the technical and economic potential to contribute to mitigation of climate change, and the costs. It also included legal and regulatory issues, public perception, environmental impacts and safety as well as issues related to inventories and accounting of greenhouse gas emission reductions.

This report primarily assesses literature published after the Third Assessment Report (2001) on CO_2 sources, capture systems, transport and various storage mechanisms. It does not cover biological carbon sequestration by land use, land use change and forestry, or by fertilization of oceans. The report builds upon the contribution of Working Group III to the Third Assessment Report Climate Change 2001 (Mitigation), and on the Special Report on Emission Scenarios of 2000, with respect to CO_2 capture and storage in a portfolio of mitigation options. It identifies those gaps in knowledge that would need to be addressed in order to facilitate large-scale deployment.

The structure of the report follows the components of a CO_2 capture and storage system. An introductory chapter outlines the general framework for the assessment and provides a brief overview of CCS systems. Chapter 2 characterizes the major sources of CO_2 that are technically and economically suitable for capture, in order to assess the feasibility of CCS on a global scale. Technological options for CO_2 capture are discussed extensively in Chapter 3, while Chapter 4 focuses on methods of CO_2 transport. In the next three chapters, each of the major storage options is then addressed: geological storage (chapter 5), ocean storage (chapter 6), and mineral carbonation and industrial uses (chapter 7). The overall costs and economic potential of CCS are discussed in Chapter 8, followed by an examination of the implications of CCS for greenhouse gas inventories and emissions accounting (chapter 9).

The report has been written by almost 100 Lead and Coordinating Lead Authors and 25 Contributing Authors, all of whom have expended a great deal of time and effort. They came from industrialized countries, developing countries, countries with economies in transition and international organizations. The report has been reviewed by more than 200 people (both individual experts and representatives of governments) from around the world. The review process was overseen by 19 Review Editors, who ensured that all comments received the proper attention.

In accordance with IPCC Procedures, the Summary for Policymakers of this report has been approved line-by-line by governments at the IPCC Working Group III Session in Montreal, Canada, from September 22-24, 2005. During the approval process the Lead Authors confirmed that the agreed text of the Summary for Policymakers is fully consistent with the underlying full report and technical summary, both of which have been accepted by governments, but remain the full responsibility of the authors.

We wish to express our gratitude to the governments that provided financial and in-kind support for the hosting of the various meetings that were essential to complete this report. We are particularly are grateful to the Canadian Government for hosting both the Workshop in Regina, November 18-22, 2002, as well as the Working Group III approval session in Montreal, September 22-24, 2005. The writing team of this report met four times to draft the report and discuss the results of the two consecutive formal IPCC review rounds. The meetings were kindly hosted by the government of Norway (Oslo, July 2003), Australia (Canberra, December 2003), Brazil (Salvador, August 2004) and Spain (Oviedo, April 2005), respectively. In addition, many individual meetings, teleconferences and interactions with governments have contributed to the successful completion of this report.

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[b] See: http://www.ipcc.ch/meet/session20/finalreport20.pdf

We endorse the words of gratitude expressed in the Foreword by the Secretary–General of the WMO and the Executive Director of UNEP to the writing team, Review Editors and Expert Reviewers.

We would like to thank the staff of the Technical Support Unit of Working Group III for their work in preparing this report, in particular Heleen de Coninck for her outstanding and efficient coordination of the report, Manuela Loos and Cora Blankendaal for their technical, logistical and secretarial support, and Leo Meyer (head of TSU) for his leadership. We also express our gratitude to Anita Meier for her general support, to Dave Thomas, Pete Thomas, Tony Cunningham, Fran Aitkens, Ann Jenks, and Ruth de Wijs for the copy-editing of the document and to Wout Niezen, Martin Middelburg, Henk Stakelbeek, Albert van Staa, Eva Stam and Tim Huliselan for preparing the final layout and the graphics of the report. A special word of thanks goes to Lee-Anne Shepherd of CO2CRC for skillfully preparing the figures in the Summary for Policymakers. Last but not least, we would like to express our appreciation to Renate Christ and her staff and to Francis Hayes of WMO for their hard work in support of the process.

We, as co-chairs of Working Group III, together with the other members of the Bureau of Working Group III, the Lead Authors and the Technical Support Unit, hope that this report will assist decision-makers in governments and the private sector as well as other interested readers in the academic community and the general public in becoming better informed about CO_2 capture and storage as a climate change mitigation option.

Ogunlade Davidson and Bert Metz
Co-Chairs IPCC Working Group III on Mitigation of Climate Change

IPCC Special Report

Carbon Dioxide Capture and Storage

Summary for Policymakers

A Special Report of Working Group III
of the Intergovernmental Panel on Climate Change

This summary, approved in detail at the Eighth Session of IPCC Working Group III (Montreal, Canada, 22-24 September 2005), represents the formally agreed statement of the IPCC concerning current understanding of carbon dioxide capture and storage.

Based on a draft by:
Juan Carlos Abanades (Spain), Makoto Akai (Japan), Sally Benson (United States), Ken Caldeira (United States), Heleen de Coninck (Netherlands), Peter Cook (Australia), Ogunlade Davidson (Sierra Leone), Richard Doctor (United States), James Dooley (United States), Paul Freund (United Kingdom), John Gale (United Kingdom), Wolfgang Heidug (Germany), Howard Herzog (United States), David Keith (Canada), Marco Mazzotti (Italy and Switzerland), Bert Metz (Netherlands), Leo Meyer (Netherlands), Balgis Osman-Elasha (Sudan), Andrew Palmer (United Kingdom), Riitta Pipatti (Finland), Edward Rubin (United States), Koen Smekens (Belgium), Mohammad Soltanieh (Iran), Kelly (Kailai) Thambimuthu (Australia and Canada)

Contents

What is CO_2 capture and storage and how could it contribute to mitigating climate change?

1. *Carbon dioxide (CO_2) capture and storage (CCS) is a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere. This report considers CCS as an option in the portfolio of mitigation actions for stabilization of atmospheric greenhouse gas concentrations.*

Other mitigation options include energy efficiency improvements, the switch to less carbon-intensive fuels, nuclear power, renewable energy sources, enhancement of biological sinks, and reduction of non-CO_2 greenhouse gas emissions. CCS has the potential to reduce overall mitigation costs and increase flexibility in achieving greenhouse gas emission reductions. The widespread application of CCS would depend on technical maturity, costs, overall potential, diffusion and transfer of the technology to developing countries and their capacity to apply the technology, regulatory aspects, environmental issues and public perception (Sections 1.1.1, 1.3, 1.7, 8.3.3.4).

2. *The Third Assessment Report (TAR) indicates that no single technology option will provide all of the emission reductions needed to achieve stabilization, but a portfolio of mitigation measures will be needed.*

Most scenarios project that the supply of primary energy will continue to be dominated by fossil fuels until at least the middle of the century. As discussed in the TAR, most models also indicate that known technological options[1] could achieve a broad range of atmospheric stabilization levels but that implementation would require socio-economic and institutional changes. In this context, the availability of CCS in the portfolio of options could facilitate achieving stabilization goals (Sections 1.1, 1.3).

What are the characteristics of CCS?

3. *Capture of CO_2 can be applied to large point sources. The CO_2 would then be compressed and transported for storage in geological formations, in the ocean, in mineral carbonates[2], or for use in industrial processes.*

Large point sources of CO_2 include large fossil fuel or biomass energy facilities, major CO_2-emitting industries, natural gas production, synthetic fuel plants and fossil fuel-based hydrogen production plants (see Table SPM.1). Potential technical storage methods are: geological storage (in geological formations, such as oil and gas fields, unminable coal beds and deep saline formations[3]), ocean storage (direct release into the ocean water column or onto the deep seafloor) and industrial fixation of CO_2 into inorganic carbonates. This report also discusses industrial uses of CO_2, but this is not expected to contribute much to the reduction of CO_2

Table SPM.1. Profile by process or industrial activity of worldwide large stationary CO_2 sources with emissions of more than 0.1 million tonnes of CO_2 ($MtCO_2$) per year.

Process	**Number of sources**	**Emissions ($MtCO_2$ yr^{-1})**
Fossil fuels		
Power	4,942	10,539
Cement production	1,175	932
Refineries	638	798
Iron and steel industry	269	646
Petrochemical industry	470	379
Oil and gas processing	Not available	50
Other sources	90	33
Biomass		
Bioethanol and bioenergy	303	91
Total	**7,887**	**13,466**

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[1] "Known technological options" refer to technologies that exist in operation or in the pilot plant stage at the present time, as referenced in the mitigation scenarios discussed in the TAR. It does not include any new technologies that.will require profound technological breakthroughs. Known technological options are explained in the TAR and several mitigation scenarios include CCS

[2] Storage of CO_2 as mineral carbonates does not cover deep geological carbonation or ocean storage with enhanced carbonate neutralization as discussed in Chapter 6 (Section 7.2).

[3] Saline formations are sedimentary rocks saturated with formation waters containing high concentrations of dissolved salts. They are widespread and contain enormous quantities of water that are unsuitable for agriculture or human consumption. Because the use of geothermal energy is likely to increase, potential geothermal areas may not be suitable for CO_2 storage (see Section 5.3.3).

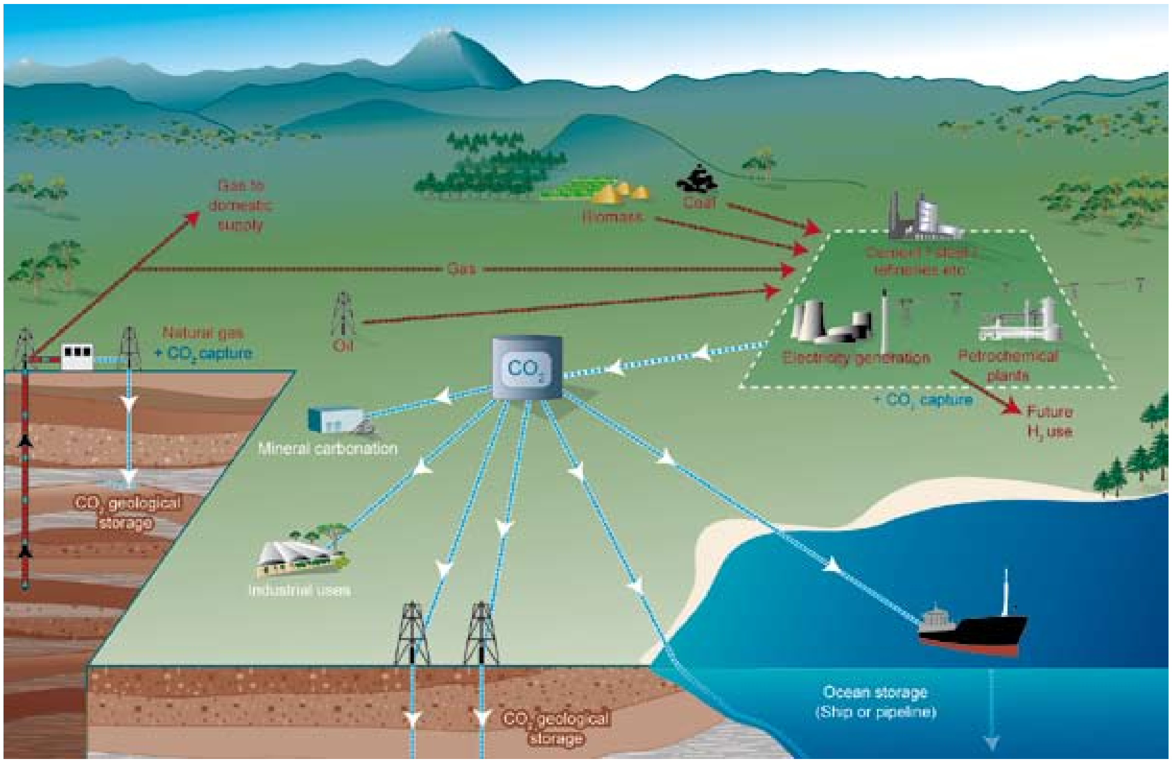

Figure SPM.1. Schematic diagram of possible CCS systems showing the sources for which CCS might be relevant, transport of CO_2 and storage options (Courtesy of CO2CRC).

emissions (see Figure SPM.1) (Sections 1.2, 1.4, 2.2, Table 2.3).

4. *The net reduction of emissions to the atmosphere through CCS depends on the fraction of CO_2 captured, the increased CO_2 production resulting from loss in overall efficiency of power plants or industrial processes due to the additional energy required for capture, transport and storage, any leakage from transport and the fraction of CO_2 retained in storage over the long term.*

Available technology captures about 85–95% of the CO_2 processed in a capture plant. A power plant equipped with a CCS system (with access to geological or ocean storage) would need roughly 10–40%[4] more energy than a plant of equivalent output without CCS, of which most is for capture and compression. For secure storage, the net result is that a power plant with CCS could reduce CO_2 emissions to the atmosphere by approximately 80–90% compared to a plant without CCS (see Figure SPM.2). To the extent that leakage might occur from a storage reservoir, the fraction retained is defined as the fraction of the cumulative amount of injected CO_2 that is retained over a specified period of time. CCS systems with storage as mineral carbonates would need 60–

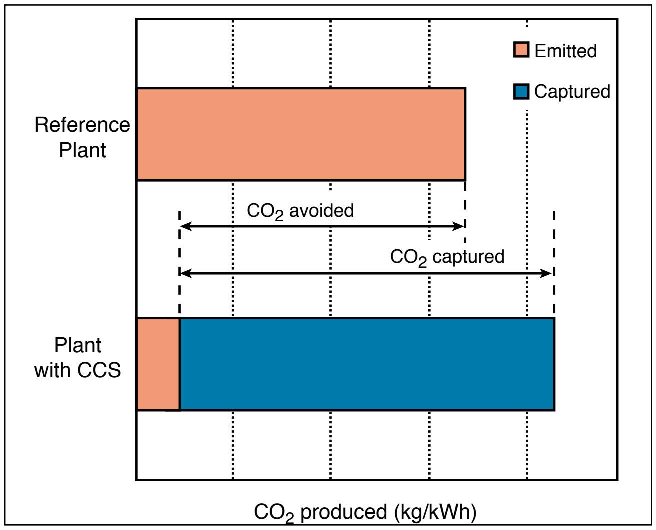

Figure SPM.2. CO_2 capture and storage from power plants. The increased CO_2 production resulting from the loss in overall efficiency of power plants due to the additional energy required for capture, transport and storage and any leakage from transport result in a larger amount of "CO_2 produced per unit of product" (lower bar) relative to the reference plant (upper bar) without capture (Figure 8.2).

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[4] The range reflects three types of power plants: for Natural Gas Combined Cycle plants, the range is 11–22%, for Pulverized Coal plants, 24–40% and for Integrated Gasification Combined Cycle plants, 14–25%.

180% more energy than a plant of equivalent output without CCS. (Sections 1.5.1, 1.6.3, 3.6.1.3, 7.2.7).

What is the current status of CCS technology?

5. *There are different types of CO_2 capture systems: post-combustion, pre-combustion and oxyfuel combustion (Figure SPM.3). The concentration of CO_2 in the gas stream, the pressure of the gas stream and the fuel type (solid or gas) are important factors in selecting the capture system.*

Post-combustion capture of CO_2 in power plants is economically feasible under specific conditions[5]. It is used to capture CO_2 from part of the flue gases from a number of existing power plants. Separation of CO_2 in the natural gas processing industry, which uses similar technology, operates in a mature market[6]. The technology required for pre-combustion capture is widely applied in fertilizer manufacturing and in hydrogen production. Although the initial fuel conversion steps of pre-combustion are more elaborate and costly, the higher concentrations of CO_2 in the gas stream and the higher pressure make the separation easier. Oxyfuel combustion is in the demonstration phase[7] and uses high purity oxygen. This results in high CO_2 concentrations in the gas stream and, hence, in easier separation of CO_2 and in increased energy requirements in the separation of oxygen from air (Sections 3.3, 3.4, 3.5).

6. *Pipelines are preferred for transporting large amounts of CO_2 for distances up to around 1,000 km. For amounts smaller than a few million tonnes of CO_2 per year or for larger distances overseas, the use of ships, where applicable, could be economically more attractive.*

Pipeline transport of CO_2 operates as a mature market technology (in the USA, over 2,500 km of pipelines transport more than 40 $MtCO_2$ per year). In most gas pipelines, compressors at the upstream end drive the flow, but some pipelines need intermediate compressor stations. Dry CO_2 is not corrosive to pipelines, even if the CO_2 contains contaminants. Where the CO_2 contains moisture, it is removed from the CO_2 stream to prevent corrosion and to avoid the costs of constructing pipelines of corrosion-

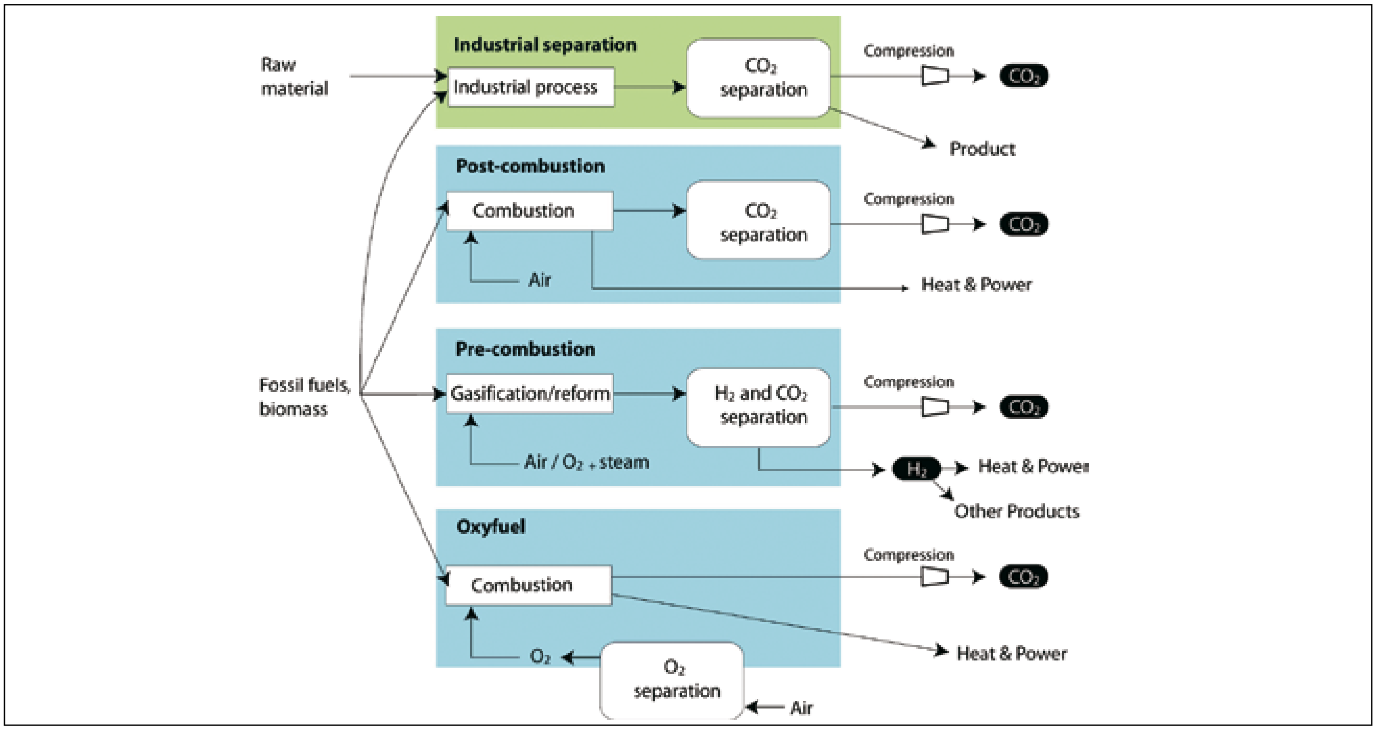

Figure SPM.3. Schematic representation of capture systems. Fuels and products are indicated for oxyfuel combustion, pre-combustion (including hydrogen and fertilizer production), post-combustion and industrial sources of CO_2 (including natural gas processing facilities and steel and cement production) (based on Figure 3.1) (Courtesy CO2CRC).

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[5] "Economically feasible under specific conditions" means that the technology is well understood and used in selected commercial applications, such as in a favourable tax regime or a niche market, processing at least 0.1 $MtCO_2\ yr^{-1}$, with few (less than 5) replications of the technology.

[6] "Mature market" means that the technology is now in operation with multiple replications of the commercial-scale technology worldwide.

[7] "Demonstration phase" means that the technology has been built and operated at the scale of a pilot plant but that further development is required before the technology is ready for the design and construction of a full-scale system.

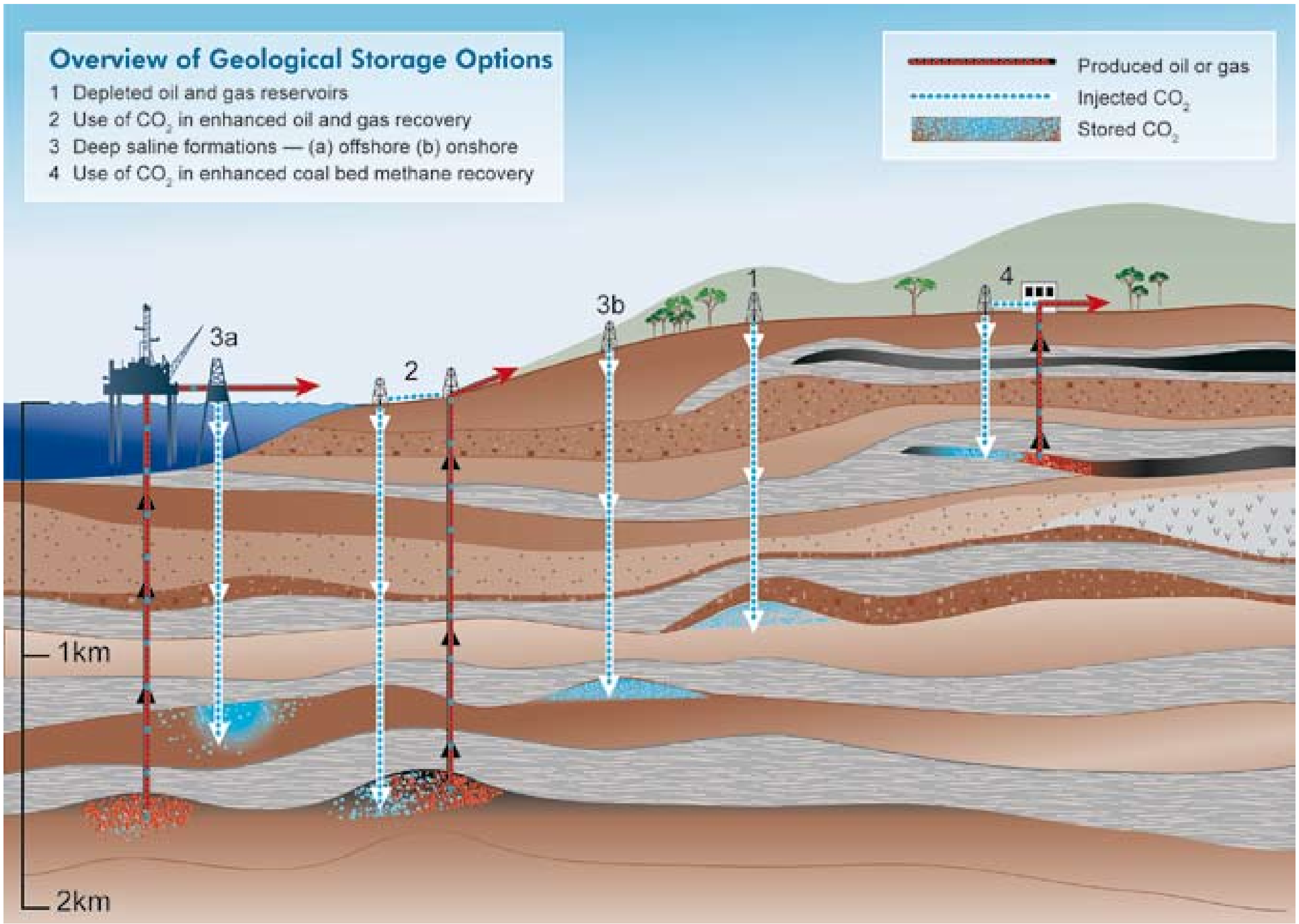

Figure SPM.4. Overview of geological storage options (based on Figure 5.3) (Courtesy CO2CRC).

resistant material. Shipping of CO_2, analogous to shipping of liquefied petroleum gases, is economically feasible under specific conditions but is currently carried out on a small scale due to limited demand. CO_2 can also be carried by rail and road tankers, but it is unlikely that these could be attractive options for large-scale CO_2 transportation (Sections 4.2.1, 4.2.2, 4.3.2, Figure 4.5, 4.6).

7. *Storage of CO_2 in deep, onshore or offshore geological formations uses many of the same technologies that have been developed by the oil and gas industry and has been proven to be economically feasible under specific conditions for oil and gas fields and saline formations, but not yet for storage in unminable coal beds*[8] *(see Figure SPM.4).*

If CO_2 is injected into suitable saline formations or oil or gas fields, at depths below 800 m[9], various physical and geochemical trapping mechanisms would prevent it from migrating to the surface. In general, an essential physical trapping mechanism is the presence of a caprock[10]. Coal bed storage may take place at shallower depths and relies on the adsorption of CO_2 on the coal, but the technical feasibility largely depends on the permeability of the coal bed. The combination of CO_2 storage with Enhanced Oil Recovery (EOR[11]) or, potentially, Enhanced Coal Bed Methane recovery (ECBM) could lead to additional revenues from the oil or gas recovery. Well-drilling technology, injection technology, computer simulation of storage reservoir performance and monitoring methods from existing applications are being

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[8] A coal bed that is unlikely to ever be mined – because it is too deep or too thin – may be potentially used for CO_2 storage. If subsequently mined, the stored CO_2 would be released. Enhanced Coal Bed Methane (ECBM) recovery could potentially increase methane production from coals while simultaneously storing CO_2. The produced methane would be used and not released to the atmosphere (Section 5.3.4).

[9] At depths below 800–1,000 m, CO_2 becomes supercritical and has a liquid-like density (about 500–800 kg m^{-3}) that provides the potential for efficient utilization of underground storage space and improves storage security (Section 5.1.1).

[10] Rock of very low permeability that acts as an upper seal to prevent fluid flow out of a reservoir.

[11] For the purposes of this report, EOR means CO_2-driven Enhanced Oil Recovery.

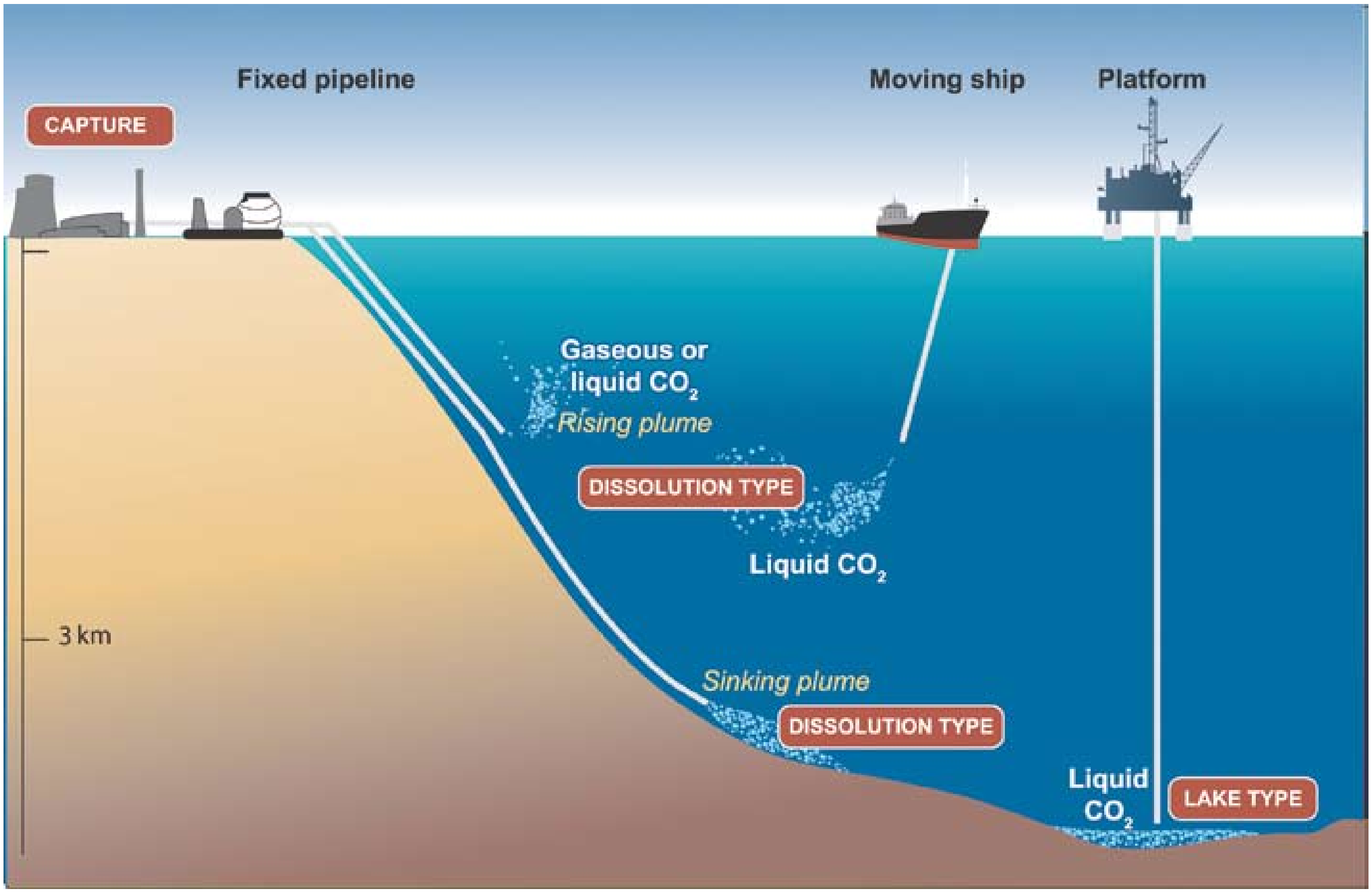

Figure SPM.5. Overview of ocean storage concepts. In "dissolution type" ocean storage, the CO_2 rapidly dissolves in the ocean water, whereas in "lake type" ocean storage, the CO_2 is initially a liquid on the sea floor (Courtesy CO2CRC).

developed further for utilization in the design and operation of geological storage projects.

Three industrial-scale[12] storage projects are in operation: the Sleipner project in an offshore saline formation in Norway, the Weyburn EOR project in Canada, and the In Salah project in a gas field in Algeria. Others are planned (Sections 5.1.1, 5.2.2, 5.3, 5.6, 5.9.4, Boxes 5.1, 5.2, 5.3).

8. *Ocean storage potentially could be done in two ways: by injecting and dissolving CO_2 into the water column (typically below 1,000 meters) via a fixed pipeline or a moving ship, or by depositing it via a fixed pipeline or an offshore platform onto the sea floor at depths below 3,000 m, where CO_2 is denser than water and is expected to form a "lake" that would delay dissolution of CO_2 into the surrounding environment (see Figure SPM.5). Ocean storage and its ecological impacts are still in the research phase*[13].

The dissolved and dispersed CO_2 would become part of the global carbon cycle and eventually equilibrate with the CO_2 in the atmosphere. In laboratory experiments, small-scale ocean experiments and model simulations, the technologies and associated physical and chemical phenomena, which include, notably, increases in acidity (lower *p*H) and their effect on marine ecosystems, have been studied for a range of ocean storage options (Sections 6.1.2, 6.2.1, 6.5, 6.7).

9. *The reaction of CO_2 with metal oxides, which are abundant in silicate minerals and available in small quantities in waste streams, produces stable carbonates. The technology is currently in the research stage, but certain applications in using waste streams are in the demonstration phase.*

The natural reaction is very slow and has to be enhanced by pre-treatment of the minerals, which at present is very energy intensive (Sections 7.2.1, 7.2.3, 7.2.4, Box 7.1).

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[12] "Industrial-scale" here means on the order of 1 $MtCO_2$ per year.

[13] "Research phase" means that while the basic science is understood, the technology is currently in the stage of conceptual design or testing at the laboratory or bench scale and has not been demonstrated in a pilot plant.

10. Industrial uses[14] of captured CO_2 as a gas or liquid or as a feedstock in chemical processes that produce valuable carbon-containing products are possible, but are not expected to contribute to significant abatement of CO_2 emissions.

The potential for industrial uses of CO_2 is small, while the CO_2 is generally retained for short periods (usually months or years). Processes using captured CO_2 as feedstock instead of fossil hydrocarbons do not always achieve net lifecycle emission reductions (Sections 7.3.1, 7.3.4).

11. Components of CCS are in various stages of development (see Table SPM.2). Complete CCS systems can be assembled from existing technologies that are mature or economically feasible under specific conditions, although the state of development of the overall system may be less than some of its separate components.

There is relatively little experience in combining CO_2 capture, transport and storage into a fully integrated CCS system. The utilization of CCS for large-scale power plants (the potential application of major interest) still remains to be implemented (Sections 1.4.4, 3.8, 5.1).

What is the geographical relationship between the sources and storage opportunities for CO_2?

12. Large point sources of CO_2 are concentrated in proximity to major industrial and urban areas. Many such sources are within 300 km of areas that potentially hold formations suitable for geological storage (see Figure SPM.6). Preliminary research suggests that, globally, a small proportion of large point sources is close to potential ocean storage locations.

Table SPM.2. Current maturity of CCS system components. The X's indicate the highest level of maturity for each component. For most components, less mature technologies also exist.

CCS component	**CCS technology**	**Research phase** [13]	**Demonstration phase** [7]	**Economically feasible under specific conditions** [5]	**Mature market** [6]
Capture	Post-combustion			X	
	Pre-combustion			X	
	Oxyfuel combustion		X		
	Industrial separation (natural gas processing, ammonia production)				X
Transportation	Pipeline				X
	Shipping			X	
Geological storage	Enhanced Oil Recovery (EOR)				X[a]
	Gas or oil fields			X	
	Saline formations			X	
	Enhanced Coal Bed Methane recovery (ECBM)		X		
Ocean storage	Direct injection (dissolution type)	X			
	Direct injection (lake type)	X			
Mineral carbonation	Natural silicate minerals	X			
	Waste materials		X		
Industrial uses of CO_2					X

[a] CO_2 injection for EOR is a mature market technology, but when this technology is used for CO_2 storage, it is only 'economically feasible under specific conditions'

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[14] Industrial uses of CO_2 refer to those uses that do not include EOR, which is discussed in paragraph 7.

Figure SPM.6a. Global distribution of large stationary sources of CO_2 (Figure 2.3) (based on a compilation of publicly available information on global emission sources; IEA GHG 2002)

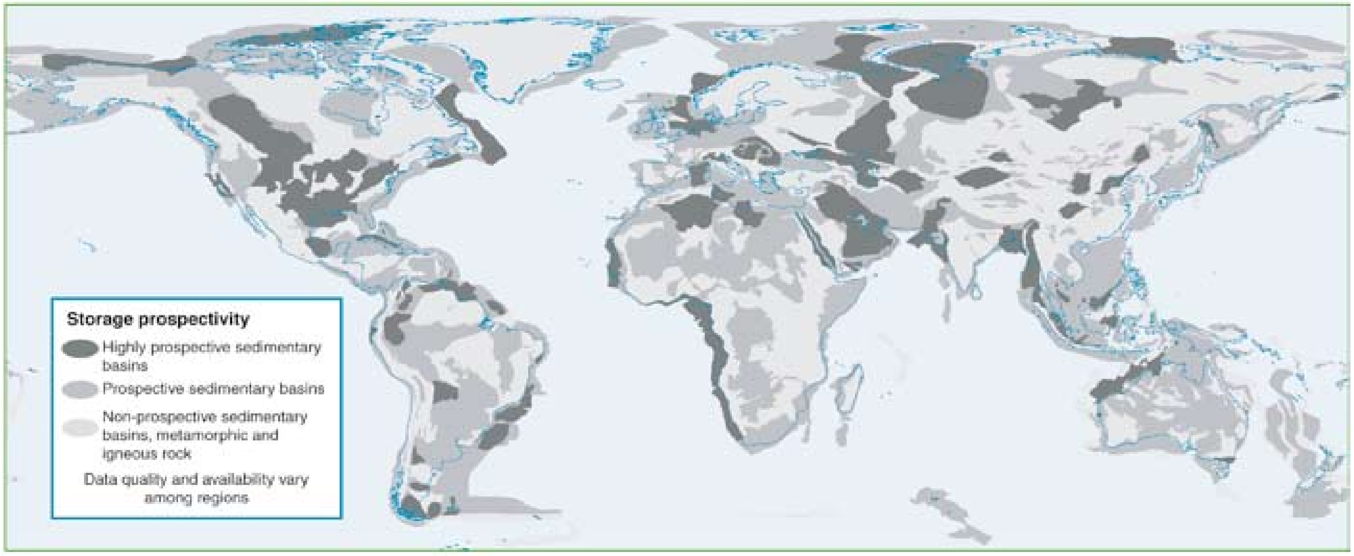

Figure SPM.6b. Prospective areas in sedimentary basins where suitable saline formations, oil or gas fields or coal beds may be found. Locations for storage in coal beds are only partly included. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present in a given area based on the available information. This figure should be taken as a guide only because it is based on partial data, the quality of which may vary from region to region and which may change over time and with new information (Figure 2.4) (Courtesy of Geoscience Australia).

Currently available literature regarding the matches between large CO_2 point sources with suitable geological storage formations is limited. Detailed regional assessments may be necessary to improve information (see Figure SPM.6b).

Scenario studies indicate that the number of large point sources is projected to increase in the future, and that, by 2050, given expected technical limitations, around 20–40% of global fossil fuel CO_2 emissions could be technically suitable for capture, including 30–60% of the CO_2 emissions from electricity generation and 30–40% of those from industry. Emissions from large-scale biomass conversion facilities could also be technically suitable for capture. The proximity of future large point sources to potential storage sites has not been studied (Sections 2.3, 2.4.3).

13. *CCS enables the control of the CO_2 emissions from fossil fuel-based production of electricity or hydrogen, which in the longer term could reduce part of the dispersed CO_2*

emissions from transport and distributed energy supply systems.

Electricity could be used in vehicles, and hydrogen could be used in fuel cells, including in the transport sector. Gas and coal conversion with integrated CO_2 separation (without storage) is currently the dominant option for the production of hydrogen. More fossil fuel or biomass-based hydrogen or electricity production would result in an increased number of large CO_2 sources that are technically suitable for capture and storage. At present, it is difficult to project the likely number, location and size of such sources (Sections 2.5.1).

What are the costs[15] for CCS and what is the technical and economic potential?

14. *Application of CCS to electricity production, under 2002 conditions, is estimated to increase electricity generation costs by about 0.01–0.05 US dollars[16] per kilowatt hour (US$/kWh), depending on the fuel, the specific technology, the location and the national circumstances. Inclusion of the benefits of EOR would reduce additional electricity production costs due to CCS by around 0.01–0.02 US$/kWh[17] (see Table SPM.3 for absolute electricity production costs and Table SPM.4 for costs in US$/t$CO_2$ avoided). Increases in market prices of fuels used for power generation would generally tend to increase the cost of CCS. The quantitative impact of oil price on CCS is uncertain. However, revenue from EOR would generally be higher with higher oil prices. While applying CCS to biomass-based power production at the current small scale would add substantially to the electricity costs, co-firing of biomass in a larger coal-fired power plant with CCS would be more cost-effective.*

Costs vary considerably in both absolute and relative terms from country to country. Since neither Natural Gas Combined Cycle, Pulverized Coal nor Integrated Gasification Combined Cycle systems have yet been built at a full scale with CCS, the costs of these systems cannot be stated with a high degree of confidence at this time. In the future, the costs of CCS could be reduced by research and technological development and economies of scale. Economies of scale could also considerably bring down the cost of biomass-based CCS systems over time. The application of CCS to biomass-fuelled or co-fired conversion facilities would lead to lower or negative[18] CO_2 emissions, which could reduce the costs for this option, depending on the market value of CO_2 emission reductions (Sections 2.5.3, 3.7.1, 3.7.13, 8.2.4).

15. *Retrofitting existing plants with CO_2 capture is expected to lead to higher costs and significantly reduced overall efficiencies than for newly built power plants with capture. The cost disadvantages of retrofitting may be reduced in the case of some relatively new and highly efficient existing plants or where a plant is substantially upgraded or rebuilt.*

The costs of retrofitting CCS to existing installations vary. Industrial sources of CO_2 can more easily be retrofitted with CO_2 separation, while integrated power plant systems would need more profound adjustment. In order to reduce future retrofit costs, new plant designs could take future CCS application into account (Sections 3.1.4, 3.7.5).

16. *In most CCS systems, the cost of capture (including compression) is the largest cost component.*

Costs for the various components of a CCS system vary widely, depending on the reference plant and the wide range

Table SPM.3. Costs of CCS: production costs of electricity for different types of generation, without capture and for the CCS system as a whole. The cost of a full CCS system for electricity generation from a newly built, large-scale fossil fuel-based power plant depends on a number of factors, including the characteristics of both the power plant and the capture system, the specifics of the storage site, the amount of CO_2 and the required transport distance. The numbers assume experience with a large-scale plant. Gas prices are assumed to be 2.8-4.4 US$ per gigajoule (GJ), and coal prices 1-1.5 US$ GJ^{-1} (based on Tables 8.3 and 8.4).

Power plant system	**Natural Gas Combined Cycle (US$/kWh)**	**Pulverized Coal (US$/kWh)**	**Integrated Gasification Combined Cycle (US$/kWh)**
Without capture (reference plant)	0.03 - 0.05	0.04 - 0.05	0.04 - 0.06
With capture and geological storage	0.04 - 0.08	0.06 - 0.10	0.05 - 0.09
With capture and EOR[17]	0.04 - 0.07	0.05 - 0.08	0.04 - 0.07

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[15] As used in this report, "costs" refer only to market prices but do not include external costs such as environmental damages and broader societal costs that may be associated with the use of CCS. To date, little has been done to assess and quantify such external costs.

[16] All costs in this report are expressed in 2002 US$.

[17] Based on oil prices of 15–20 US$ per barrel, as used in the available literature.

[18] If, for example, the biomass is harvested at an unsustainable rate (that is, faster than the annual re-growth), the net CO_2 emissions of the activity might not be negative.

Table SPM.4. CO_2 avoidance costs for the complete CCS system for electricity generation, for different combinations of reference power plants without CCS and power plants with CCS (geological and EOR). The amount of CO_2 avoided is the difference between the emissions of the reference plant and the emissions of the power plant with CCS. Gas prices are assumed to be 2.8-4.4 US\$ GJ^{-1}, and coal prices 1-1.5 US\$ GJ^{-1} (based on Tables 8.3a and 8.4).

Type of power plant with CCS	Natural Gas Combined Cycle reference plant US\$/tCO_2 avoided	Pulverized Coal reference plant US\$/tCO_2 avoided
Power plant with capture and geological storage		
Natural Gas Combined Cycle	40 - 90	20 - 60
Pulverized Coal	70 - 270	30 - 70
Integrated Gasification Combined Cycle	40 - 220	20 - 70
Power plant with capture and EOR[17]		
Natural Gas Combined Cycle	20 - 70	0 - 30
Pulverized Coal	50 - 240	10 - 40
Integrated Gasification Combined Cycle	20 - 190	0 - 40

Table SPM.5. 2002 Cost ranges for the components of a CCS system as applied to a given type of power plant or industrial source. The costs of the separate components cannot simply be summed to calculate the costs of the whole CCS system in US\$/CO_2 avoided. All numbers are representative of the costs for large-scale, new installations, with natural gas prices assumed to be 2.8-4.4 US\$ GJ^{-1} and coal prices 1-1.5 US\$ GJ^{-1} (Sections 5.9.5, 8.2.1, 8.2.2, 8.2.3, Tables 8.1 and 8.2).

CCS system components	Cost range	Remarks
Capture from a coal- or gas-fired power plant	15-75 US\$/tCO_2 net captured	Net costs of captured CO_2, compared to the same plant without capture.
Capture from hydrogen and ammonia production or gas processing	5-55 US\$/tCO_2 net captured	Applies to high-purity sources requiring simple drying and compression.
Capture from other industrial sources	25-115 US\$/tCO_2 net captured	Range reflects use of a number of different technologies and fuels.
Transportation	1-8 US\$/tCO_2 transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) MtCO_2 yr^{-1}.
Geological storage[a]	0.5-8 US\$/tCO_2 net injected	Excluding potential revenues from EOR or ECBM.
Geological storage: monitoring and verification	0.1-0.3 US\$/tCO_2 injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements.
Ocean storage	5-30 US\$/tCO_2 net injected	Including offshore transportation of 100-500 km, excluding monitoring and verification.
Mineral carbonation	50-100 US\$/tCO_2 net mineralized	Range for the best case studied. Includes additional energy use for carbonation.

[a] Over the long term, there may be additional costs for remediation and liabilities.

in CO_2 source, transport and storage situations (see Table SPM.5). Over the next decade, the cost of capture could be reduced by 20–30%, and more should be achievable by new technologies that are still in the research or demonstration phase. The costs of transport and storage of CO_2 could decrease slowly as the technology matures further and the scale increases (Sections 1.5.3, 3.7.13, 8.2).

17. *Energy and economic models indicate that the CCS system's major contribution to climate change mitigation would come from deployment in the electricity sector. Most modelling as assessed in this report suggests that CCS systems begin to deploy at a significant level when CO_2 prices begin to reach approximately 25–30 US\$/tCO_2.*
Low-cost capture possibilities (in gas processing and in hydrogen and ammonia manufacture, where separation of CO_2 is already done) in combination with short (<50 km) transport distances and storage options that generate revenues (such as EOR) can lead to the limited storage of CO_2 (up to 360 MtCO_2 yr^{-1}) under circumstances of low or no incentives (Sections 2.2.1.3, 2.3, 2.4, 8.3.2.1)

18. Available evidence suggests that, worldwide, it is likely[19] *that there is a technical potential*[20] *of at least about 2,000* $GtCO_2$ *(545 GtC) of storage capacity in geological formations*[21].

There could be a much larger potential for geological storage in saline formations, but the upper limit estimates are uncertain due to lack of information and an agreed methodology. The capacity of oil and gas reservoirs is better known. Technical storage capacity in coal beds is much smaller and less well known.

Model calculations for the capacity to store CO_2 in the oceans indicate that this capacity could be on the order of thousands of $GtCO_2$, depending on the assumed stabilization level in the atmosphere[22] and on environmental constraints such as ocean *p*H change. The extent to which mineral carbonation may be used can currently not be determined, since it depends on the unknown amount of silicate reserves that can be technically exploited and on environmental issues such as the volume of product disposal (Sections 5.3, 6.3.1, 7.2.3, Table 5.2).

19. In most scenarios for stabilization of atmospheric greenhouse gas concentrations between 450 and 750 ppmv CO_2 *and in a least-cost portfolio of mitigation options, the economic potential*[23] *of CCS would amount to 220–2,200* $GtCO_2$ *(60–600 GtC) cumulatively, which would mean that CCS contributes 15–55% to the cumulative mitigation effort worldwide until 2100, averaged over a range of baseline scenarios. It is likely*[20] *that the technical potential*[21] *for geological storage is sufficient to cover the high end of the economic potential range, but for specific regions, this may not be true.*

Uncertainties in these economic potential estimates are significant. For CCS to achieve such an economic potential, several hundreds to thousands of CO_2 capture systems would need to be installed over the coming century, each capturing some 1–5 $MtCO_2$ per year. The actual implementation of CCS, as for other mitigation options, is likely to be lower than the economic potential due to factors such as environmental impacts, risks of leakage and the lack of a clear legal framework or public acceptance (Sections 1.4.4, 5.3.7, 8.3.1, 8.3.3, 8.3.3.4).

20. In most scenario studies, the role of CCS in mitigation portfolios increases over the course of the century, and the inclusion of CCS in a mitigation portfolio is found to reduce the costs of stabilizing CO_2 *concentrations by 30% or more.*

One aspect of the cost competitiveness of CCS systems is that CCS technologies are compatible with most current energy infrastructures.

The global potential contribution of CCS as part of a mitigation portfolio is illustrated by the examples given in Figure SPM.7. The present extent of analyses in this field is limited, and further assessments may be necessary to improve information (Sections 1.5, 8.3.3, 8.3.3.4, Box 8.3).

What are the local health, safety and environment risks of CCS?

21. The local risks[24] *associated with* CO_2 *pipeline transport could be similar to or lower than those posed by hydrocarbon pipelines already in operation.*

For existing CO_2 pipelines, mostly in areas of low population density, accident numbers reported per kilometre pipeline are very low and are comparable to those for hydrocarbon pipelines. A sudden and large release of CO_2 would pose immediate dangers to human life and health, if there were exposure to concentrations of CO_2 greater than 7–10% by volume in air. Pipeline transport of CO_2 through populated areas requires attention to route selection, overpressure protection, leak detection and other design factors. No major obstacles to pipeline design for CCS are foreseen (Sections 4.4.2, AI.2.3.1).

22. With appropriate site selection based on available subsurface information, a monitoring programme to detect problems, a regulatory system and the appropriate use of remediation methods to stop or control CO_2 *releases if they arise, the local health, safety and environment risks of geological storage would be comparable to the risks of current activities such as natural gas storage, EOR and deep underground disposal of acid gas.*

Natural CO_2 reservoirs contribute to the understanding of the behaviour of CO_2 underground. Features of storage sites with a low probability of leakage include highly impermeable caprocks, geological stability, absence of leakage paths

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[19] "Likely" is a probability between 66 and 90%.

[20] "Technical potential" as defined in the TAR is the amount by which it is possible to reduce greenhouse gas emissions by implementing a technology or practice that already has been demonstrated

[21] This statement is based on the expert judgment of the authors of the available literature. It reflects the uncertainty about the storage capacity estimates (Section 5.3.7)

[22] This approach takes into account that the CO_2 injected in the ocean will after some time reach equilibrium with the atmosphere.

[23] Economic potential is the amount of greenhouse gas emissions reductions from a specific option that could be achieved cost-effectively, given prevailing circumstances (i.e. a market value of CO_2 reductions and costs of other options).

[24] In discussing the risks, we assume that risk is the product of the probability that an event will occur and the consequences of the event if it does occur.

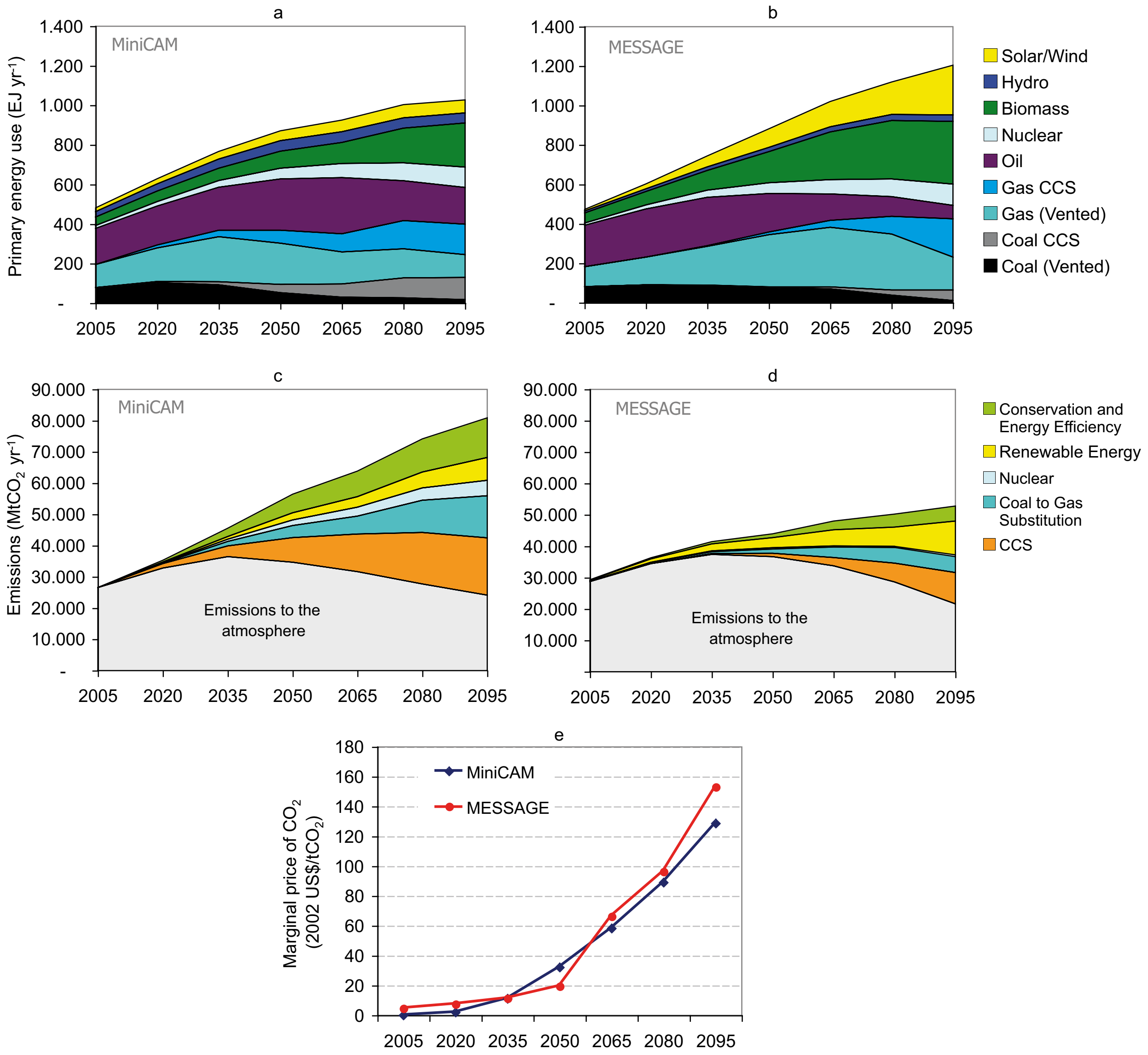

Figure SPM.7. These figures are an illustrative example of the global potential contribution of CCS as part of a mitigation portfolio. They are based on two alternative integrated assessment models (MESSAGE and MiniCAM) while adopt the same assumptions for the main emissions drivers. The results would vary considerably on regional scales. This example is based on a single scenario and, therefore, does not convey the full range of uncertainties. Panels a and b show global primary energy use, including the deployment of CCS. Panels c and d show the global CO_2 emissions in grey and corresponding contributions of main emissions reduction measures in colour. Panel e shows the calculated marginal price of CO_2 reductions (Section 8.3.3, Box 8.3).

and effective trapping mechanisms. There are two different types of leakage scenarios: (1) abrupt leakage, through injection well failure or leakage up an abandoned well, and (2) gradual leakage, through undetected faults, fractures or wells. Impacts of elevated CO_2 concentrations in the shallow subsurface could include lethal effects on plants and subsoil animals and the contamination of groundwater. High fluxes in conjunction with stable atmospheric conditions could lead to local high CO_2 concentrations in the air that could harm animals or people. Pressure build-up caused by CO_2 injection could trigger small seismic events.

While there is limited experience with geological storage, closely related industrial experience and scientific knowledge could serve as a basis for appropriate risk management, including remediation. The effectiveness of the available risk management methods still needs to be demonstrated for use with CO_2 storage. If leakage occurs at a storage site, remediation to stop the leakage could involve standard well repair techniques or the interception and extraction of the CO_2 before it would leak into a shallow groundwater aquifer. Given the long timeframes associated with geological storage of CO_2, site monitoring may be required for very long periods (Sections 5.6, 5.7, Tables 5.4, 5.7, Figure 5.25).

23. *Adding CO_2 to the ocean or forming pools of liquid CO_2 on the ocean floor at industrial scales will alter the local chemical environment. Experiments have shown that sustained high concentrations of CO_2 would cause mortality of ocean organisms. CO_2 effects on marine organisms will have ecosystem consequences. The chronic effects of direct CO_2 injection into the ocean on ecosystems over large ocean areas and long time scales have not yet been studied.*

Model simulations, assuming a release from seven locations at an ocean depth of 3,000 m, where ocean storage provides 10% of the mitigation effort for stabilization at 550 ppmv CO_2, resulted in acidity increases (pH decrease >0.4) over approximately 1% of the ocean volume. For comparison purposes: in such a stabilization case without ocean storage, a pH decrease >0.25 relative to pre-industrial levels at the entire ocean surface can be expected. A 0.2 to 0.4 pH decrease is significantly greater than pre-industrial variations in average ocean acidity. At these levels of pH change, some effects have been found in organisms that live near the ocean's surface, but chronic effects have not yet been studied. A better understanding of these impacts is required before a comprehensive risk assessment can be accomplished. There is no known mechanism for the sudden or catastrophic release of stored CO_2 from the ocean to the atmosphere. Gradual release is discussed in SPM paragraph 26. Conversion of molecular CO_2 to bicarbonates or hydrates before or during CO_2 release would reduce the pH effects and enhance the retention of CO_2 in the ocean, but this would also increase the costs and other environmental impacts (Section 6.7).

24. *Environmental impacts of large-scale mineral carbonation would be a consequence of the required mining and disposal of resulting products that have no practical use.*

Industrial fixation of one tonne of CO_2 requires between 1.6 and 3.7 tonnes of silicate rock. The impacts of mineral carbonation are similar to those of large-scale surface mines. They include land-clearing, decreased local air quality and affected water and vegetation as a result of drilling, moving of earth and the grading and leaching of metals from mining residues, all of which indirectly may also result in habitat degradation. Most products of mineral carbonation need to be disposed of, which would require landfills and additional transport (Sections 7.2.4, 7.2.6).

Will physical leakage of stored CO_2 compromise CCS as a climate change mitigation option?

25. *Observations from engineered and natural analogues as well as models suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely[25] to exceed 99% over 100 years and is likely[20] to exceed 99% over 1,000 years.*

For well-selected, designed and managed geological storage sites, the vast majority of the CO_2 will gradually be immobilized by various trapping mechanisms and, in that case, could be retained for up to millions of years. Because of these mechanisms, storage could become more secure over longer timeframes (Sections 1.6.3, 5.2.2, 5.7.3.4, Table 5.5).

26. *Release of CO_2 from ocean storage would be gradual over hundreds of years.*

Ocean tracer data and model calculations indicate that, in the case of ocean storage, depending on the depth of injection and the location, the fraction retained is 65–100% after 100 years and 30–85% after 500 years (a lower percentage for injection at a depth of 1,000 m, a higher percentage at 3,000 m) (Sections 1.6.3, 6.3.3, 6.3.4, Table 6.2)

27. *In the case of mineral carbonation, the CO_2 stored would not be released to the atmosphere (Sections 1.6.3, 7.2.7).*

28. *If continuous leakage of CO_2 occurs, it could, at least in part, offset the benefits of CCS for mitigating climate change. Assessments of the implications of leakage for climate change mitigation depend on the framework chosen for decision-making and on the information available on the fractions retained for geological or ocean storage as presented in paragraphs 25 and 26.*

Studies conducted to address the question of how to deal with non-permanent storage are based on different approaches: the value of delaying emissions, cost minimization of a specified mitigation scenario or allowable future emissions in the context of an assumed stabilization of atmospheric greenhouse gas concentrations. Some of these studies allow future leakage to be compensated by additional reductions in emissions; the results depend on assumptions regarding the future cost of reductions, discount rates, the amount of CO_2 stored and the atmospheric concentration stabilization level assumed. In other studies, compensation is not seen as an option because of political and institutional uncertainties, and the analysis focuses on limitations set by the assumed

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[25] "Very likely" is a probability between 90 and 99%.

stabilization level and the amount stored. While specific results of the range of studies vary with the methods and assumptions made, all studies imply that, if CCS is to be acceptable as a mitigation measure, there must be an upper limit to the amount of leakage that can take place (Sections 1.6.4, 8.4).

What are the legal and regulatory issues for implementing CO_2 storage?

29. *Some regulations for operations in the subsurface do exist that may be relevant or, in some cases, directly applicable to geological storage, but few countries have specifically developed legal or regulatory frameworks for long-term CO_2 storage.*

Existing laws and regulations regarding inter alia mining, oil and gas operations, pollution control, waste disposal, drinking water, treatment of high-pressure gases and subsurface property rights may be relevant to geological CO_2 storage. Long-term liability issues associated with the leakage of CO_2 to the atmosphere and local environmental impacts are generally unresolved. Some States take on long-term responsibility in situations comparable to CO_2 storage, such as underground mining operations (Sections 5.8.2, 5.8.3, 5.8.4).

30. *No formal interpretations so far have been agreed upon with respect to whether or under what conditions CO_2 injection into the geological sub-seabed or the ocean is compatible.*

There are currently several treaties (notably the London[26] and OSPAR[27] Conventions) that potentially apply to the injection of CO_2 into the geological sub-seabed or the ocean. All of these treaties have been drafted without specific consideration of CO_2 storage (Sections 5.8.1, 6.8.1).

What are the implications of CCS for emission inventories and accounting?

31. *The current IPCC Guidelines[28] do not include methods specific to estimating emissions associated with CCS.*

The general guidance provided by the IPCC can be applied to CCS. A few countries currently do so, in combination with their national methods for estimating emissions. The IPCC guidelines themselves do not yet provide specific methods for estimating emissions associated with CCS. These are expected to be provided in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Specific methods may be required for the net capture and storage of CO_2, physical leakage, fugitive emissions and negative emissions associated with biomass applications of CCS systems (Sections 9.2.1, 9.2.2).

32. *The few current CCS projects all involve geological storage, and there is therefore limited experience with the monitoring, verification and reporting of actual physical leakage rates and associated uncertainties.*

Several techniques are available or under development for monitoring and verification of CO_2 emissions from CCS, but these vary in applicability, site specificity, detection limits and uncertainties (Sections 9.2.3, 5.6, 6.6.2).

33. *CO_2 might be captured in one country and stored in another with different commitments. Issues associated with accounting for cross-border storage are not unique to CCS.*

Rules and methods for accounting may have to be adjusted accordingly. Possible physical leakage from a storage site in the future would have to be accounted for (Section 9.3).

What are the gaps in knowledge?

34. *There are gaps in currently available knowledge regarding some aspects of CCS. Increasing knowledge and experience would reduce uncertainties and thus facilitate decision-making with respect to the deployment of CCS for climate change mitigation (Section TS.10).*

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[26] Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972), and its London Protocol (1996), which has not yet entered into force.

[27] Convention for the Protection of the Marine Environment of the North-East Atlantic, which was adopted in Paris (1992). OSPAR is an abbreviation of Oslo-Paris.

[28] Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, and Good Practice Guidance Reports; Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, and Good Practice Guidance for Land Use, Land-Use Change and Forestry

IPCC Special Report

Carbon Dioxide Capture and Storage

Technical Summary

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Contents

1. Introduction and framework of this report

Carbon dioxide capture and storage (CCS), the subject of this Special Report, is considered as one of the options for reducing atmospheric emissions of CO_2 from human activities. The purpose of this Special Report is to assess the current state of knowledge regarding the technical, scientific, environmental, economic and societal dimensions of CCS and to place CCS in the context of other options in the portfolio of potential climate change mitigation measures.

The structure of this Technical Summary follows that of the Special Report. This introductory section presents the general framework for the assessment together with a brief overview of CCS systems. Section 2 then describes the major sources of CO_2, a step needed to assess the feasibility of CCS on a global scale. Technological options for CO_2 capture are then discussed in Section 3, while Section 4 focuses on methods of CO_2 transport. Following this, each of the storage options is addressed. Section 5 focuses on geological storage, Section 6 on ocean storage, and Section 7 on mineral carbonation and industrial uses of CO_2. The overall costs and economic potential of CCS are then discussed in Section 8, followed by an examination in Section 9 of the implications of CCS for greenhouse gas emissions inventories and accounting. The Technical Summary concludes with a discussion of gaps in knowledge, especially those critical for policy considerations.

Overview of CO_2 capture and storage

CO_2 is emitted principally from the burning of fossil fuels, both in large combustion units such as those used for electric power generation and in smaller, distributed sources such as automobile engines and furnaces used in residential and commercial buildings. CO_2 emissions also result from some industrial and resource extraction processes, as well as from the burning of forests during land clearance. CCS would most likely be applied to large point sources of CO_2, such as power plants or large industrial processes. Some of these sources could supply decarbonized fuel such as hydrogen to the transportation, industrial and building sectors, and thus reduce emissions from those distributed sources.

CCS involves the use of technology, first to collect and concentrate the CO_2 produced in industrial and energy-related sources, transport it to a suitable storage location, and then store it away from the atmosphere for a long period of time. CCS would thus allow fossil fuels to be used with low emissions of greenhouse gases. Application of CCS to biomass energy sources could result in the net removal of CO_2 from the atmosphere (often referred to as 'negative emissions') by capturing and storing the atmospheric CO_2 taken up by the biomass, provided the biomass is not harvested at an unsustainable rate.

Figure TS.1 illustrates the three main components of the CCS process: capture, transport and storage. All three components are found in industrial operations today, although mostly not for the purpose of CO_2 storage. The capture step involves separating CO_2 from other gaseous products. For fuel-burning processes such as those in power plants, separation technologies can be used to capture CO_2 after combustion or to decarbonize the fuel before combustion. The transport step may be required to carry captured CO_2 to a suitable storage site located at a distance from the CO_2 source. To facilitate both transport and storage, the captured CO_2 gas is typically compressed to a high density at the capture facility. Potential storage methods include injection into underground geological formations, injection into the deep ocean, or industrial fixation in inorganic carbonates. Some industrial processes also might utilize and store small amounts of captured CO_2 in manufactured products.

The technical maturity of specific CCS system components varies greatly. Some technologies are extensively deployed in mature markets, primarily in the oil and gas industry, while others are still in the research, development or demonstration phase. Table TS.1 provides an overview of the current status of all CCS components. As of mid-2005, there have been three commercial projects linking CO_2 capture and geological storage: the offshore Sleipner natural gas processing project in Norway, the Weyburn Enhanced Oil Recovery (EOR)[1] project in Canada (which stores CO_2 captured in the United States) and the In Salah natural gas project in Algeria. Each captures and stores 1–2 $MtCO_2$ per year. It should be noted, however, that CCS has not yet been applied at a large (e.g., 500 MW) fossil-fuel power plant, and that the overall system may not be as mature as some of its components.

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[1] In this report, EOR means enhanced oil recovery using CO_2

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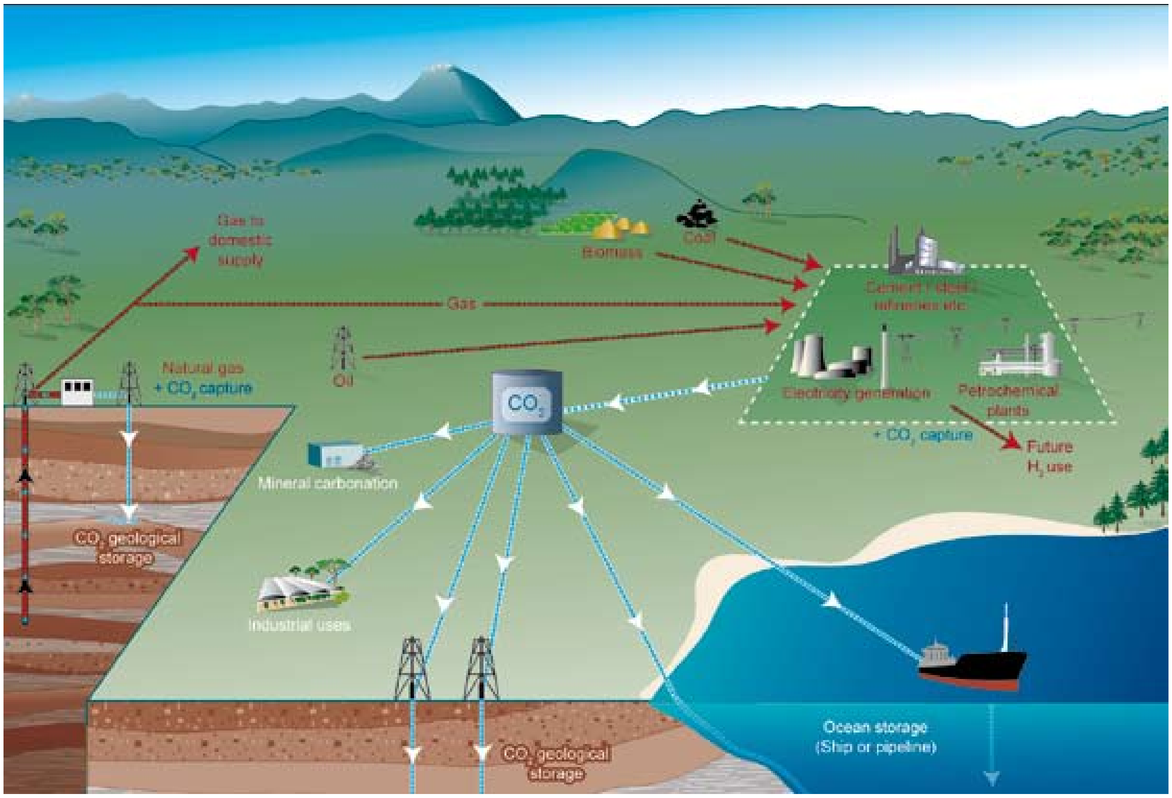

Figure TS.1. Schematic diagram of possible CCS systems. It shows the sources for which CCS might be relevant, as well as CO_2 transport and storage options (Courtesy CO2CRC).

Why the interest in CO_2 capture and storage?

In 1992, international concern about climate change led to the United Nations Framework Convention on Climate Change (UNFCCC). The ultimate objective of that Convention is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system". From this perspective, the context for considering CCS (and other mitigation options) is that of a world constrained in CO_2 emissions, consistent with the international goal of stabilizing atmospheric greenhouse gas concentrations. Most scenarios for global energy use project a substantial increase of CO_2 emissions throughout this century in the absence of specific actions to mitigate climate change. They also suggest that the supply of primary energy will continue to be dominated by fossil fuels until at least the middle of the century (see Section 8). The magnitude of the emissions reduction needed to stabilize the atmospheric concentration of CO_2 will depend on both the level of future emissions (the baseline) and the desired target for long-term CO_2 concentration: the lower the stabilization target and the higher the baseline emissions, the larger the required reduction in CO_2 emissions. IPCC's Third Assessment Report (TAR) states that, depending on the scenario considered, cumulative emissions of hundreds or even thousands of gigatonnes of CO_2 would need to be prevented during this century to stabilize the CO_2 concentration at 450 to 750 ppmv[2]. The TAR also finds that, "most model results indicate that known technological options[3] could achieve a broad range of atmospheric CO_2 stabilization levels", but that "no single technology option will provide all of the emissions reductions needed". Rather, a combination of mitigation measures will be needed to achieve stabilization. These known technological options are available for stabilization, although the TAR cautions that, "implementation would require associated socio-economic and institutional changes".

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[2] ppmv is parts per million by volume.

[3] "Known technological options" refer to technologies that are currently at the operation or pilot-plant stages, as referred to in the mitigation scenarios discussed in IPCC's Third Assessment Report. The term does not include any new technologies that will require drastic technological breakthroughs. It can be considered to represent a conservative estimate given the length of the scenario period.

Table TS.1. Current maturity of CCS system components. An X indicates the highest level of maturity for each component. There are also less mature technologies for most components.

CCS component	CCS technology	Research phase [a]	Demonstration phase [b]	Economically feasible under specific conditions [c]	Mature market [d]
Capture	Post-combustion			X	
	Pre-combustion			X	
	Oxyfuel combustion		X		
	Industrial separation (natural gas processing, ammonia production)				X
Transportation	Pipeline				X
	Shipping			X	
Geological storage	Enhanced Oil Recovery (EOR)				X[e]
	Gas or oil fields			X	
	Saline formations			X	
	Enhanced Coal Bed Methane recovery (ECBM)[f]		X		
Ocean storage	Direct injection (dissolution type)	X			
	Direct injection (lake type)	X			
Mineral carbonation	Natural silicate minerals	X			
	Waste materials		X		
Industrial uses of CO_2					X

[a] Research phase means that the basic science is understood, but the technology is currently in the stage of conceptual design or testing at the laboratory or bench scale, and has not been demonstrated in a pilot plant.

[b] Demonstration phase means that the technology has been built and operated at the scale of a pilot plant, but further development is required before the technology is required before the technology is ready for the design and construction of a full-scale system.

[c] Economically feasible under specific conditions means that the technology is well understood and used in selected commercial applications, for instance if there is a favourable tax regime or a niche market, or processing on in the order of 0.1 $MtCO_2$ yr^{-1}, with few (less than 5) replications of the technology.

[d] Mature market means that the technology is now in operation with multiple replications of the technology worldwide.

[e] CO_2 injection for EOR is a mature market technology, but when used for CO_2 storage, it is only economically feasible under specific conditions.

[f] ECBM is the use of CO_2 to enhance the recovery of the methane present in unminable coal beds through the preferential adsorption of CO_2 on coal. Unminable coal beds are unlikely to ever be mined, because they are too deep or too thin. If subsequently mined, the stored CO_2 would be released.

In this context, the availability of CCS in the portfolio of options for reducing greenhouse gas emissions could facilitate the achievement of stabilization goals. Other technological options, which have been examined more extensively in previous IPCC assessments, include: (1) reducing energy demand by increasing the efficiency of energy conversion and/or utilization devices; (2) decarbonizing energy supplies (either by switching to less carbon-intensive fuels (coal to natural gas, for example), and/or by increasing the use of renewable energy sources and/or nuclear energy (each of which, on balance, emit little or no CO_2); (3) sequestering CO_2 through the enhancement of natural sinks by biological fixation; and (4) reducing non-CO_2 greenhouse gases. Model results presented later in this report suggest that use of CCS in conjunction with other measures could significantly reduce the cost of achieving stabilization and would increase flexibility in achieving these reductions . The heavy worldwide reliance on fossil fuels today (approximately 80% of global energy use), the potential for CCS to reduce CO_2 emissions over the next century, and the compatibility of CCS systems with current energy infrastructures explain the interest in this technology.

Major issues for this assessment

There are a number of issues that need to be addressed in trying to understand the role that CCS could play in mitigating climate change. Questions that arise, and that are addressed in different sections of this Technical Summary, include the following:

- What is the current status of CCS technology?
- What is the potential for capturing and storing CO_2?
- What are the costs of implementation?
- How long should CO_2 be stored in order to achieve significant climate change mitigation?
- What are the health, safety and environment risks of CCS?
- What can be said about the public perception of CCS?
- What are the legal issues for implementing CO_2 storage?
- What are the implications for emission inventories and accounting?
- What is the potential for the diffusion and transfer of CCS technology?

When analyzing CCS as an option for climate change mitigation, it is of central importance that all resulting emissions from the system, especially emissions of CO_2, be identified and assessed in a transparent way. The importance of taking a "systems" view of CCS is therefore stressed, as the selection of an appropriate system boundary is essential for proper analysis. Given the energy requirements associated with capture and some storage and utilization options, and the possibility of leaking storage reservoirs, it is vital to assess the CCS chain as a whole.

From the perspectives of both atmospheric stabilization and long-term sustainable development, CO_2 storage must extend over time scales that are long enough to contribute significantly to climate change mitigation. This report expresses the duration of CO_2 storage in terms of the'fraction retained', defined as the fraction of the cumulative mass of CO_2 injected that is retained in a storage reservoir over a specified period of time. Estimates of such fractions for different time periods and storage options are presented later. Questions arise not only about how long CO_2 will remain stored, but also what constitutes acceptable amounts of slow, continuous leakage[4] from storage. Different approaches to this question are discussed in Section 8.

CCS would be an option for countries that have significant sources of CO_2 suitable for capture, that have access to storage sites and experience with oil or gas operations, and that need to satisfy their development aspirations in a carbon-constrained environment. Literature assessed in the IPCC Special Report 'Methodological and Technological Issues and Technology Transfer' indicates that there are many potential barriers that could inhibit deployment in developing countries, even of technologies that are mature in industrialized countries. Addressing these barriers and creating conditions that would facilitate diffusion of the technology to developing countries would be a major issue for the adoption of CCS worldwide.

2. Sources of CO_2

This section describes the major current anthropogenic sources of CO_2 emissions and their relation to potential storage sites. As noted earlier, CO_2 emissions from human activity arise from a number of different sources, mainly from the combustion of fossil fuels used in power generation, transportation, industrial processes, and residential and commercial buildings. CO_2 is also emitted during certain industrial processes like cement manufacture or hydrogen production and during the combustion of biomass. Future emissions are also discussed in this section.

Current CO_2 sources and characteristics

To assess the potential of CCS as an option for reducing global CO_2 emissions, the current global geographical relationship between large stationary CO_2 emission sources and their proximity to potential storage sites has been examined. CO_2 emissions in the residential, commerical and transportation sectors have not been considered in this analysis because these emission sources are individually small and often mobile, and therefore unsuitable for capture and storage. The discussion here also includes an analysis of potential future sources of CO_2 based on several scenarios of future global energy use and emissions over the next century.

Globally, emissions of CO_2 from fossil-fuel use in the year 2000 totalled about 23.5 $GtCO_2\ yr^{-1}$ (6 $GtC\ yr^{-1}$). Of this, close to 60% was attributed to large (>0.1 $MtCO_2\ yr^{-1}$) stationary emission sources (see Table TS.2). However, not all of these sources are amenable to CO_2 capture. Although the sources evaluated are distributed throughout the world, the database reveals four particular clusters of emissions: North America (midwest and eastern USA), Europe (northwest region), East Asia (eastern coast of China) and South Asia (Indian subcontinent). By contrast, large-scale biomass sources are much smaller in number and less globally distributed.

Currently, the vast majority of large emission sources have CO_2 concentrations of less than 15% (in some cases, substantially less). However, a small portion (less than 2%) of the fossil fuel-based industrial sources have CO_2 concentrations in excess of 95%. The high-concentration sources are potential candidates for the early implementation

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[4] With respect to CO_2 storage, leakage is defined as the escape of injected fluid from storage. This is the most common meaning used in this Summary. If used in the context of trading of carbon dioxide emission reductions, it may signify the change in anthropogenic emissions by sources or removals by sinks which occurs outside the project boundary.

Table TS.2. Profile by process or industrial activity of worldwide large stationary CO_2 sources with emissions of more than 0.1 $MtCO_2$ per year.

Process	Number of sources	Emissions ($MtCO_2$ yr^{-1})
Fossil fuels		
Power	4,942	10,539
Cement production	1,175	932
Refineries	638	798
Iron and steel industry	269	646
Petrochemical industry	470	379
Oil and gas processing	N/A	50
Other sources	90	33
Biomass		
Bioethanol and bioenergy	303	91
Total	**7,887**	**13,466**

of CCS because only dehydration and compression would be required at the capture stage (see Section 3). An analysis of these high-purity sources that are within 50 km of storage formations and that have the potential to generate revenues (via the use of CO_2 for enhanced hydrocarbon production through ECBM or EOR) indicates that such sources currently emit approximately 360 $MtCO_2$ per year. Some biomass sources like bioethanol production also generate high-concentration CO_2 sources which could also be used in similar applications.

The distance between an emission location and a storage site can have a significant bearing on whether or not CCS can play a significant role in reducing CO_2 emissions. Figure TS.2a depicts the major CO_2 emission sources (indicated by dots), and Figure TS.2b shows the sedimentary basins with geological storage prospectivity (shown in different shades of grey). In broad terms, these figures indicate that there is potentially good correlation between major sources and prospective sedimentary basins, with many sources lying either directly above, or within reasonable distances (less than 300 km) from areas with potential for geological storage. The basins shown in Figure TS.2b have not been identified or evaluated as suitable storage reservoirs; more detailed geological analysis on a regional level is required to confirm the suitability of these potential storage sites.

Figure TS.2a. Global distribution of large stationary sources of CO_2 (based on a compilation of publicly available information on global emission sources, IEA GHG 2002)

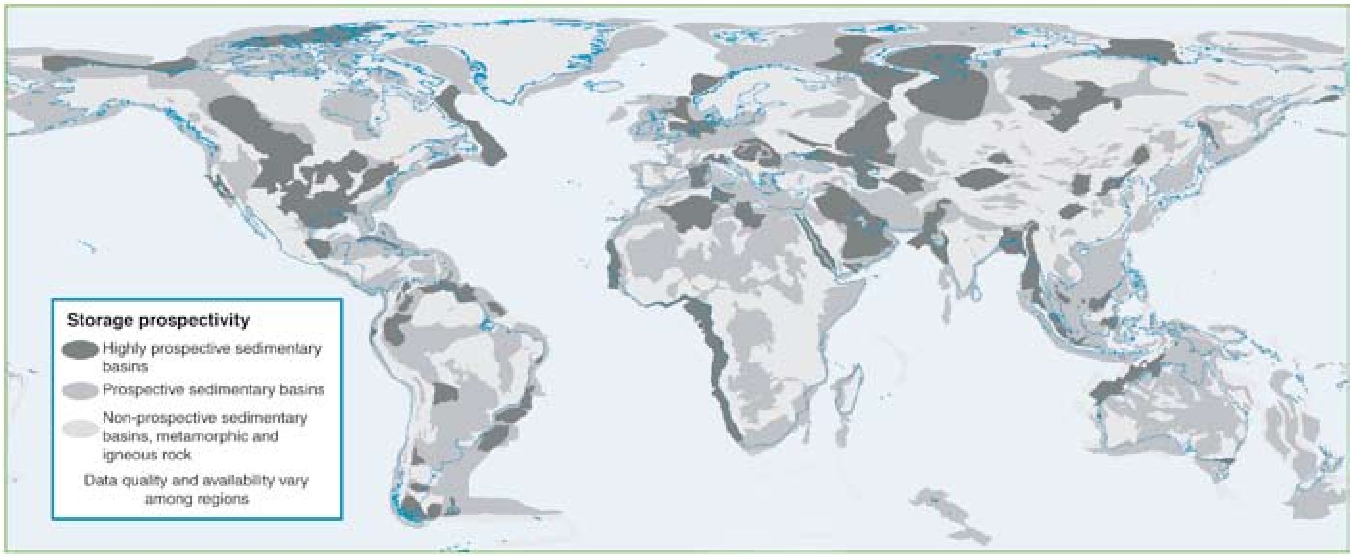

Figure TS.2b. Prospective areas in sedimentary basins where suitable saline formations, oil or gas fields, or coal beds may be found. Locations for storage in coal beds are only partly included. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present in a given area based on the available information. This figure should be taken as a guide only, because it is based on partial data, the quality of which may vary from region to region, and which may change over time and with new information (Courtesy of Geoscience Australia).

Future emission sources

In the IPCC Special Report on Emission Scenarios (SRES), the future emissions of CO_2 are projected on the basis of six illustrative scenarios in which global CO_2 emissions range from 29 to 44 $GtCO_2$ (8–12 GtC) per year in 2020, and from 23 to 84 $GtCO_2$ (6–23 GtC) per year in 2050. It is projected that the number of CO_2 emission sources from the electric power and industrial sectors will increase significantly until 2050, mainly in South and East Asia. By contrast, the number of such sources in Europe may decrease slightly. The proportion of sources with high and low CO_2 content will be a function of the size and rate of introduction of plants employing gasification or liquefaction of fossil fuels to produce hydrogen, or other liquid and gaseous products. The greater the number of these plants, the greater the number of sources with high CO_2 concentrations technically suitable for capture.

The projected potential of CO_2 capture associated with the above emission ranges has been estimated at an annual 2.6 to 4.9 $GtCO_2$ by 2020 (0.7–1.3 GtC) and 4.7 to 37.5 $GtCO_2$ by 2050 (1.3–10 GtC). These numbers correspond to 9–12%, and 21–45% of global CO_2 emissions in 2020 and 2050, respectively. The emission and capture ranges reflect the inherent uncertainties of scenario and modelling analyses, and the technical limitations of applying CCS. These scenarios only take into account CO_2 capture from fossil fuels, and not from biomass sources. However, emissions from large-scale biomass conversion facilities could also be technically suitable for capture.

The potential development of low-carbon energy carriers is relevant to the future number and size of large, stationary CO_2 sources with high concentrations. Scenarios also suggest that large-scale production of low-carbon energy carriers such as electricity or hydrogen could, within several decades, begin displacing the fossil fuels currently used by small, distributed sources in residential and commercial buildings and in the transportation sector (see Section 8). These energy carriers could be produced from fossil fuels and/or biomass in large plants that would generate large point sources of CO_2 (power plants or plants similar to current plants producing hydrogen from natural gas). These sources would be suitable for CO_2 capture. Such applications of CCS could reduce dispersed CO_2 emissions from transport and from distributed energy supply systems. At present, however, it is difficult to project the likely number, size, or geographical distribution of the sources associated with such developments.

3. Capture of CO_2

This section examines CCS capture technology. As shown in Section 2, power plants and other large-scale industrial processes are the primary candidates for capture and the main focus of this section.

Capture technology options and applications

The purpose of CO_2 capture is to produce a concentrated stream of CO_2 at high pressure that can readily be transported to a storage site. Although, in principle, the entire gas stream containing low concentrations of CO_2 could be transported and injected underground, energy costs and other associated costs generally make this approach impractical. It is therefore necessary to produce a nearly pure CO_2 stream for transport and storage. Applications separating CO_2 in large industrial plants, including natural gas treatment plants and ammonia production facilities, are already in operation today. Currently, CO_2 is typically removed to purify other industrial gas streams. Removal has been used for storage purposes in only a few cases; in most cases, the CO_2 is emitted to the atmosphere. Capture processes also have been used to obtain commercially useful amounts of CO_2 from flue gas streams generated by the combustion of coal or natural gas. To date, however, there have been no applications of CO_2 capture at large (e.g., 500 MW) power plants.

Depending on the process or power plant application in question, there are three main approaches to capturing the CO_2 generated from a primary fossil fuel (coal, natural gas or oil), biomass, or mixtures of these fuels:

Post-combustion systems separate CO_2 from the flue gases produced by the combustion of the primary fuel in air. These systems normally use a liquid solvent to capture the small fraction of CO_2 (typically 3–15% by volume) present in a flue gas stream in which the main constituent is nitrogen (from air). For a modern pulverized coal (PC) power plant or a natural gas combined cycle (NGCC) power plant, current post-combustion capture systems would typically employ an organic solvent such as monoethanolamine (MEA).

Pre-combustion systems process the primary fuel in a reactor with steam and air or oxygen to produce a mixture consisting mainly of carbon monoxide and hydrogen ("synthesis gas"). Additional hydrogen, together with CO_2, is produced by reacting the carbon monoxide with steam in a second reactor (a "shift reactor"). The resulting mixture of hydrogen and CO_2 can then be separated into a CO_2 gas stream, and a stream of hydrogen. If the CO_2 is stored, the hydrogen is a carbon-free energy carrier that can be combusted to generate power and/or heat. Although the initial fuel conversion steps are more elaborate and costly than in post-combustion systems, the high concentrations of CO_2 produced by the shift reactor (typically 15 to 60% by volume on a dry basis) and the high pressures often encountered in these applications are more favourable for CO_2 separation. Pre-combustion would be used at power plants that employ integrated gasification combined cycle (IGCC) technology.

Oxyfuel combustion systems use oxygen instead of air for combustion of the primary fuel to produce a flue gas that is mainly water vapour and CO_2. This results in a flue gas with high CO_2 concentrations (greater than 80% by volume). The water vapour is then removed by cooling and compressing the gas stream. Oxyfuel combustion requires the upstream separation of oxygen from air, with a purity of 95–99% oxygen assumed in most current designs. Further treatment of the flue gas may be needed to remove air pollutants and non-condensed gases (such as nitrogen) from the flue gas before the CO_2 is sent to storage. As a method of CO_2 capture in boilers, oxyfuel combustion systems are in the demonstration phase (see Table TS.1). Oxyfuel systems are also being studied in gas turbine systems, but conceptual designs for such applications are still in the research phase.

Figure TS.3 shows a schematic diagram of the main capture processes and systems. All require a step involving the separation of CO_2, H_2 or O_2 from a bulk gas stream (such as flue gas, synthesis gas, air or raw natural gas). These separation steps can be accomplished by means of physical or chemical solvents, membranes, solid sorbents, or by cryogenic separation. The choice of a specific capture technology is determined largely by the process conditions under which it must operate. Current post-combustion and pre-combustion systems for power plants could capture 85–95% of the CO_2 that is produced. Higher capture efficiencies are possible, although separation devices become considerably larger, more energy intensive and more costly. Capture and compression need roughly 10–40% more energy than the equivalent plant without capture, depending on the type of system. Due to the associated CO_2 emissions, the net amount of CO_2 captured is approximately 80–90%. Oxyfuel combustion systems are, in principle, able to capture nearly all of the CO_2 produced. However, the need for additional gas treatment systems to remove pollutants such as sulphur and nitrogen oxides lowers the level of CO_2 captured to slightly more than 90%.

As noted in Section 1, CO_2 capture is already used in several industrial applications (see Figure TS.4). The same technologies as would be used for pre-combustion capture are employed for the large-scale production of hydrogen (which is used mainly for ammonia and fertilizer manufacture, and for petroleum refinery operations). The separation of CO_2 from raw natural gas (which typically contains significant amounts of CO_2) is also practised on a large scale, using technologies similar to those used for post-combustion capture. Although commercial systems are also available for large-scale oxygen separation, oxyfuel combustion for CO_2 capture is currently in the demonstration phase. In addition, research is being conducted to achieve higher levels of system integration, increased efficiency and reduced cost for all types of capture systems.

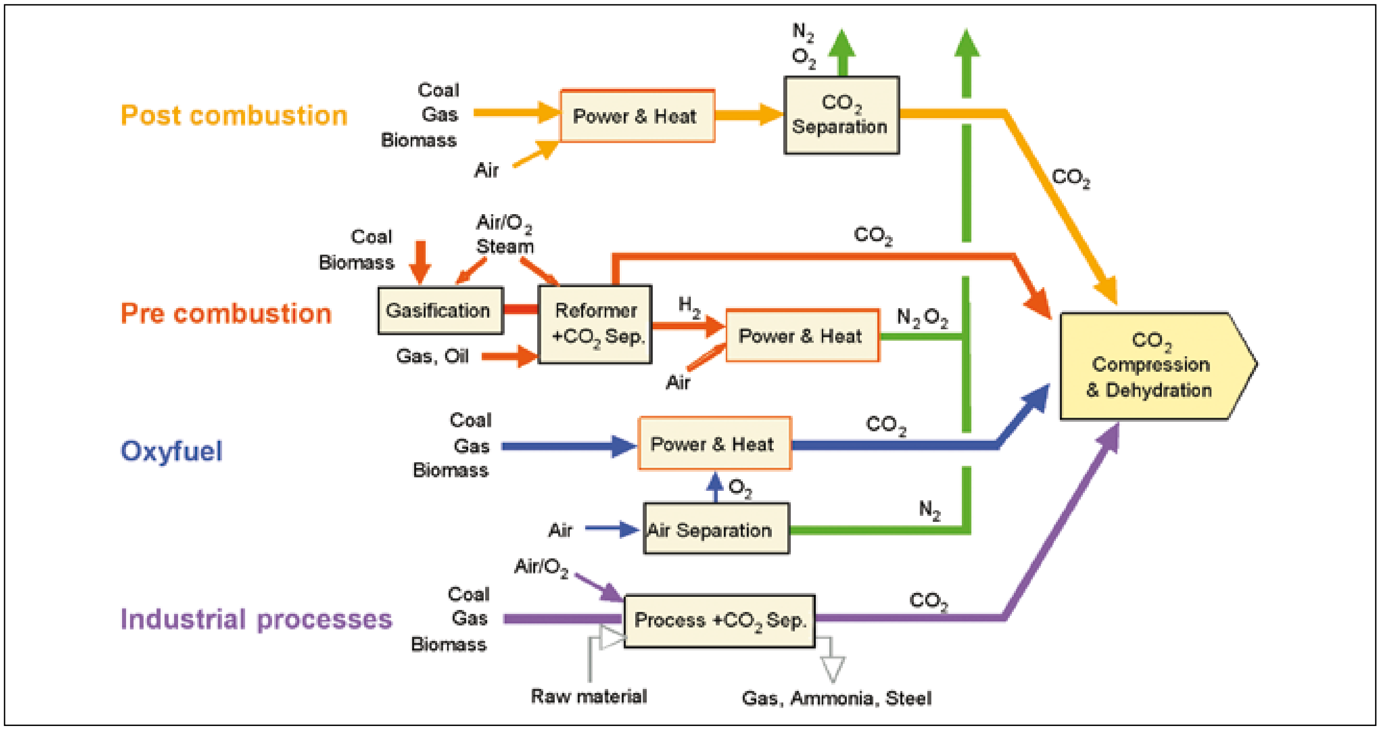

Figure TS.3. Overview of CO_2 capture processes and systems.

Figure TS.4. (a) CO_2 post-combustion capture at a plant in Malaysia. This plant employs a chemical absorption process to separate 0.2 $MtCO_2$ per year from the flue gas stream of a gas-fired power plant for urea production (Courtesy of Mitsubishi Heavy Industries). (b) CO_2 pre-combustion capture at a coal gasification plant in North Dakota, USA. This plant employs a physical solvent process to separate 3.3 $MtCO_2$ per year from a gas stream to produce synthetic natural gas. Part of the captured CO_2 is used for an EOR project in Canada.

CO_2 capture: risks, energy and the environment

The monitoring, risk and legal implications of CO_2 capture systems do not appear to present fundamentally new challenges, as they are all elements of regular health, safety and environmental control practices in industry. However, CO_2 capture systems require significant amounts of energy for their operation. This reduces net plant efficiency, so power plants require more fuel to generate each kilowatt-hour of electricity produced. Based on a review of the literature, the increase in fuel consumption per kWh for plants capturing 90% CO_2 using best current technology ranges from 24–40% for new supercritical PC plants, 11–22% for NGCC plants, and 14–25% for coal-based IGCC systems compared to similar plants without CCS. The increased fuel requirement results in an increase in most other environmental emissions per kWh generated relative to new state-of-the-art plants without CO_2 capture and, in the case of coal, proportionally larger amounts of solid wastes. In addition, there is an increase in the consumption of chemicals such as ammonia and limestone used by PC plants for nitrogen oxide and sulphur dioxide emissions control. Advanced plant designs that further reduce CCS energy requirements will also reduce overall environmental impacts as well as cost. Compared to many older existing plants, more efficient new or rebuilt plants with CCS may actually yield net reductions in plant-level environmental emissions.

Costs of CO_2 capture

The estimated costs of CO_2 capture at large power plants are based on engineering design studies of technologies in commercial use today (though often in different applications and/or at smaller scales than those assumed in the literature), as well as on design studies for concepts currently in the research and development (R&D) stage. Table TS.3 summarizes the results for new supercritical PC, NGCC and IGCC plants based on current technology with and without CO_2 capture. Capture systems for all three designs reduce CO_2 emissions per kWh by approximately 80–90%, taking into account the energy requirements for capture. All data for PC and IGCC plants in Table TS.3 are for bituminous coals only. The capture costs include the cost of compressing CO_2 (typically to about 11–14 MPa) but do not include the additional costs of CO_2 transport and storage (see Sections 4–7).

The cost ranges for each of the three systems reflect differences in the technical, economic and operating assumptions employed in different studies. While some differences in reported costs can be attributed to differences in the design of CO_2 capture systems, the major sources of variability are differences in the assumed design, operation and financing of the reference plant to which the capture technology is applied (factors such as plant size, location, efficiency, fuel type, fuel cost, capacity factor and cost of capital). No single set of assumptions applies to all situations or all parts of the world, so a range of costs is given.

For the studies listed in Table TS.3, CO_2 capture increases the cost of electricity production[5] by 35–70% (0.01 to 0.02 US\$/kWh) for an NGCC plant, 40–85% (0.02 to 0.03 US\$/kWh) for a supercritical PC plant, and 20–55% (0.01 to 0.02 US\$/kWh) for an IGCC plant. Overall, the electricity production costs for fossil fuel plants with capture (excluding CO_2 transport and storage costs) ranges from 0.04–0.09 US\$/kWh, as compared to 0.03–0.06 US\$/kWh for similar plants without capture. In most studies to date, NGCC systems have typically been found to have lower electricity production costs than new PC and IGCC plants (with or without capture) in the case of large base-load plants with high capacity factors (75% or more) and natural gas prices between 2.6 and 4.4 US\$ GJ^{-1} over the life of the plant. However, in the case of higher gas prices and/or lower capacity factors, NGCC plants often have higher electricity production costs than coal-based plants, with or without capture. Recent studies also found that IGCC plants were on average slightly more costly without capture and slightly less costly with capture than similarly-sized PC plants. However, the difference in cost between PC and IGCC plants with or without CO_2 capture can vary significantly according to coal type and other local factors, such as the cost of capital for each plant type. Since full-scale NGCC, PC and IGCC systems have not yet been built with CCS, the absolute or relative costs of these systems cannot be stated with a high degree of confidence at this time.

The costs of retrofitting existing power plants with CO_2 capture have not been extensively studied. A limited number of reports indicate that retrofitting an amine scrubber to an existing plant results in greater efficiency loss and higher costs than those shown in Table TS.3. Limited studies also indicate that a more cost-effective option is to combine a capture system retrofit with rebuilding the boiler and turbine to increase plant efficiency and output. For some existing plants, studies indicate that similar benefits could be achieved by repowering with an IGCC system that includes CO_2 capture technology. The feasibility and cost of all these options is highly dependent on site-specific factors, including the size, age and efficiency of the plant, and the availability of additional space.

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[5] The cost of electricity production should not be confused with the price of electricity to customers.

Table TS.3. Summary of CO_2 capture costs for new power plants based on current technology. Because these costs do not include the costs (or credits) for CO_2 transport and storage, this table should not be used to assess or compare total plant costs for different systems with capture. The full costs of CCS plants are reported in Section 8.

Performance and cost measures	**New NGCC plant**			**New PC plant**			**New IGCC plant**		
	Range		**Rep.**	**Range**		**Rep.**	**Range**		**Rep.**
	Low	**High**	**value**	**Low**	**High**	**value**	**Low**	**High**	**value**
Emission rate without capture (kgCO_2/kWh)	0.344	0.379	0.367	0.736	0.811	0.762	0.682	0.846	0.773
Emission rate with capture (kgCO_2/kWh)	0.040	0.066	0.052	0.092	0.145	0.112	0.065	0.152	0.108
Percentage CO_2 reduction per kWh (%)	83	88	86	81	88	85	81	91	86
Plant efficiency with capture, LHV basis (%)	47	50	48	30	35	33	31	40	35
Capture energy requirement (% increase input/kWh)	11	22	16	24	40	31	14	25	19
Total capital requirement without capture (US$/kW)	515	724	568	1161	1486	1286	1169	1565	1326
Total capital requirement with capture (US$/kW)	909	1261	998	1894	2578	2096	1414	2270	1825
Percent increase in capital cost with capture (%)	64	100	76	44	74	63	19	66	37
COE without capture (US$/kWh)	0.031	0.050	0.037	0.043	0.052	0.046	0.041	0.061	0.047
COE with capture only (US$/kWh)	0.043	0.072	0.054	0.062	0.086	0.073	0.054	0.079	0.062
Increase in COE with capture (US$/kWh)	0.012	0.024	0.017	0.018	0.034	0.027	0.009	0.022	0.016
Percent increase in COE with capture (%)	37	69	46	42	66	57	20	55	33
Cost of net CO_2 captured (US$/t$CO_2$)	37	74	53	29	51	41	13	37	23
Capture cost confidence level (see Table 3.6)	moderate			moderate			moderate		

Abbreviations: Representative value is based on the average of the values in the different studies. COE=cost of electricity production; LHV=lower heating value. See Section 3.6.1 for calculation of energy requirement for capture plants.

Notes: Ranges and representative values are based on data from Special Report Tables 3.7, 3.9 and 3.10. All PC and IGCC data are for bituminous coals only at costs of 1.0-1.5 US$ GJ^{-1} (LHV); all PC plants are supercritical units. NGCC data based on natural gas prices of 2.8-4.4 US$ GJ^{-1} (LHV basis). Cost are stated in constant US$2002. Power plant sizes range from approximately 400-800 MW without capture and 300-700 MW with capture. Capacity factors vary from 65-85% for coal plants and 50-95% for gas plants (average for each=80%). Fixed charge factors vary from 11-16%. All costs include CO_2 compression but not additional CO_2 transport and storage costs.

Table TS.4 illustrates the cost of CO_2 capture in the production of hydrogen. Here, the cost of CO_2 capture is mainly due to the cost of CO_2 drying and compression, since CO_2 separation is already carried out as part of the hydrogen production process. The cost of CO_2 capture adds approximately 5% to 30% to the cost of the hydrogen produced.

CCS also can be applied to systems that use biomass fuels or feedstock, either alone or in combination with fossil fuels. A limited number of studies have looked at the costs of such systems combining capture, transport and storage. The capturing of 0.19 MtCO_2 yr^{-1} in a 24 MWe biomass IGCC plant is estimated to be about 80 US$/t$CO_2$ net captured (300 US$/tC), which corresponds to an increase in electricity production costs of about 0.08 US$/kWh. There are relatively few studies of CO_2 capture for other industrial processes using fossil fuels and they are typically limited to capture costs reported only as a cost per tonne of CO_2 captured or avoided. In general, the CO_2 produced in different processes varies widely in pressure and concentration (see Section 2). As a result, the cost of capture in different processes (cement and steel plants, refineries), ranges widely from about 25–115 US$/t$CO_2$ net captured. The unit cost of capture is generally lower for processes where a relatively pure CO_2 stream is produced (e.g. natural gas processing, hydrogen production and ammonia production), as seen for the hydrogen plants

Table TS.4. Summary of CO_2 capture costs for new hydrogen plants based on current technology

Performance and cost measures	**New hydrogen plant**			
	Range			**Representative value**
	Low		**High**	
Emission rate without capture ($kgCO_2\ GJ^{-1}$)	78	-	174	137
Emission rate with capture ($kgCO_2\ GJ^{-1}$)	7	-	28	17
Percent CO_2 reduction per GJ (%)	72	-	96	86
Plant efficiency with capture, LHV basis (%)	52	-	68	60
Capture energy requirement (% more input GJ^{-1})	4	-	22	8
Cost of hydrogen without capture (US$ GJ^{-1})	6.5	-	10.0	7.8
Cost of hydrogen with capture (US$ GJ^{-1})	7.5	-	13.3	9.1
Increase in H_2 cost with capture (US$ GJ^{-1})	0.3	-	3.3	1.3
Percent increase in H_2 cost with capture (%)	5	-	33	15
Cost of net CO_2 captured (US$/$tCO_2$)	2	-	56	15
Capture cost confidence level	moderate to high			

Notes: Ranges and representative values are based on data from Table 3.11. All costs in this table are for capture only and do not include the costs of CO_2 transport and storage. Costs are in constant US$2002. Hydrogen plant feedstocks are natural gas (4.7-5.3 US$ GJ^{-1}) or coal (0.9-1.3 US$ GJ^{-1}); some plants in dataset produce electricity in addition to hydrogen. Fixed charge factors vary from 13-20%. All costs include CO_2 compression but not additional CO_2 transport and storage costs (see Section 8 for full CCS costs).

in Table TS.4, where costs vary from 2–56 US$/$tCO_2$ net captured.

New or improved methods of CO_2 capture, combined with advanced power systems and industrial process designs, could reduce CO_2 capture costs and energy requirements. While costs for first-of-a-kind commercial plants often exceed initial cost estimates, the cost of subsequent plants typically declines as a result of learning-by-doing and other factors. Although there is considerable uncertainty about the magnitude and timing of future cost reductions, the literature suggests that, provided R&D efforts are sustained, improvements to commercial technologies can reduce current CO_2 capture costs by at least 20–30% over approximately the next ten years, while new technologies under development could achieve more substantial cost reductions. Future cost reductions will depend on the deployment and adoption of commercial technologies in the marketplace as well as sustained R&D.

4. Transport of CO_2

Except when plants are located directly above a geological storage site, captured CO_2 must be transported from the point of capture to a storage site. This section reviews the principal methods of CO_2 transport and assesses the health, safety and environment aspects, and costs.

Methods of CO_2 transport

Pipelines today operate as a mature market technology and are the most common method for transporting CO_2. Gaseous CO_2 is typically compressed to a pressure above 8 MPa in order to avoid two-phase flow regimes and increase the density of the CO_2, thereby making it easier and less costly to transport. CO_2 also can be transported as a liquid in ships, road or rail tankers that carry CO_2 in insulated tanks at a temperature well below ambient, and at much lower pressures.

The first long-distance CO_2 pipeline came into operation in the early 1970s. In the United States, over 2,500 km of pipeline transports more than 40 $MtCO_2$ per year from natural and anthropogenic sources, mainly to sites in Texas, where the CO_2 is used for EOR.These pipelines operate in the ‘dense phase’ mode (in which there is a continuous progression from gas to liquid, without a distinct phase change), and at ambient temperature and high pressure. In most of these pipelines, the flow is driven by compressors at the upstream end, although some pipelines have intermediate (booster) compressor stations.

In some situations or locations, transport of CO_2 by ship may be economically more attractive, particularly when the CO_2 has to be moved over large distances or overseas. Liquefied petroleum gases (LPG, principally propane and butane) are transported on a large commercial scale by marine tankers. CO_2 can be transported by ship in much the same way (typically at 0.7 MPa pressure), but this currently takes place on a small scale because of limited demand. The properties of liquefied CO_2 are similar to those of LPG, and the technology could be scaled up to large CO_2 carriers if a demand for such systems were to materialize.

Road and rail tankers also are technically feasible options. These systems transport CO_2 at a temperature of -20ºC and at 2 MPa pressure. However, they are uneconomical compared to pipelines and ships, except on a very small scale, and are unlikely to be relevant to large-scale CCS.

Environment, safety and risk aspects

Just as there are standards for natural gas admitted to pipelines, so minimum standards for 'pipeline quality' CO_2 should emerge as the CO_2 pipeline infrastructure develops further. Current standards, developed largely in the context of EOR applications, are not necessarily identical to what would be required for CCS. A low-nitrogen content is important for EOR, but would not be so significant for CCS. However, a CO_2 pipeline through populated areas might need a lower specified maximum H_2S content. Pipeline transport of CO_2 through populated areas also requires detailed route selection, over-pressure protection, leak detection and other design factors. However, no major obstacles to pipeline design for CCS are foreseen.

CO_2 could leak to the atmosphere during transport, although leakage losses from pipelines are very small. Dry (moisture-free) CO_2 is not corrosive to the carbon-manganese steels customarily used for pipelines, even if the CO_2 contains contaminants such as oxygen, hydrogen sulphide, and sulphur or nitrogen oxides. Moisture-laden CO_2, on the other hand, is highly corrosive, so a CO_2 pipeline in this case would have to be made from a corrosion-resistant alloy, or be internally clad with an alloy or a continuous polymer coating. Some pipelines are made from corrosion-resistant alloys, although the cost of materials is several times larger than carbon-manganese steels. For ships, the total loss to the atmosphere is between 3 and 4% per 1000 km, counting both boil-off and the exhaust from ship engines. Boil-off could be reduced by capture and liquefaction, and recapture would reduce the loss to 1 to 2% per 1000 km.

Accidents can also occur. In the case of existing CO_2 pipelines, which are mostly in areas of low population density, there have been fewer than one reported incident per year (0.0003 per km-year) and no injuries or fatalities. This is consistent with experience with hydrocarbon pipelines, and the impact would probably not be more severe than for natural gas accidents. In marine transportation, hydrocarbon gas tankers are potentially dangerous, but the recognized hazard has led to standards for design, construction and operation, and serious incidents are rare.

Cost of CO_2 transport

Costs have been estimated for both pipeline and marine transportation of CO_2. In every case the costs depend strongly on the distance and the quantity transported. In the case of pipelines, the costs depend on whether the pipeline is onshore or offshore, whether the area is heavily congested, and whether there are mountains, large rivers, or frozen ground on the route. All these factors could double the cost per unit length, with even larger increases for pipelines in populated areas. Any additional costs for recompression (booster pump stations) that may be needed for longer pipelines would be counted as part of transport costs. Such costs are relatively small and not included in the estimates presented here.

Figure TS.5 shows the cost of pipeline transport for a nominal distance of 250 km. This is typically 1–8 US\$/tCO_2 (4–30 US\$/tC). The figure also shows how pipeline cost depends on the CO_2 mass flow rate. Steel cost accounts for a significant fraction of the cost of a pipeline, so fluctuations in such cost (such as the doubling in the years from 2003 to 2005) could affect overall pipeline economics.

In ship transport, the tanker volume and the characteristics of the loading and unloading systems are some of the key factors determining the overall transport cost.

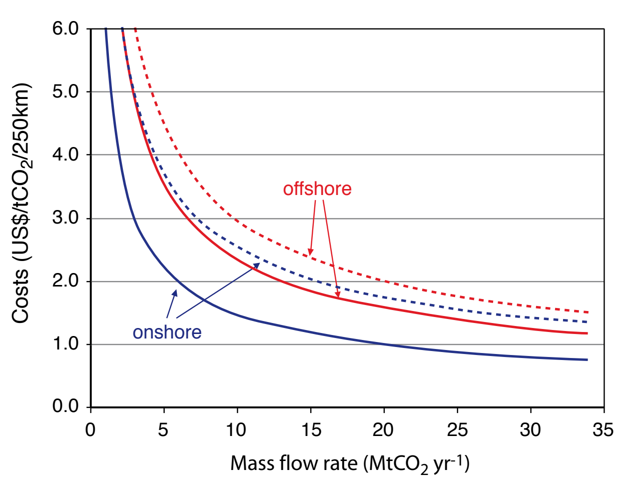

Figure TS.5. Transport costs for onshore pipelines and offshore pipelines, in US\$ per tCO_2 per 250 km as a function of the CO_2 mass flow rate. The graph shows high estimates (dotted lines) and low estimates (solid lines).

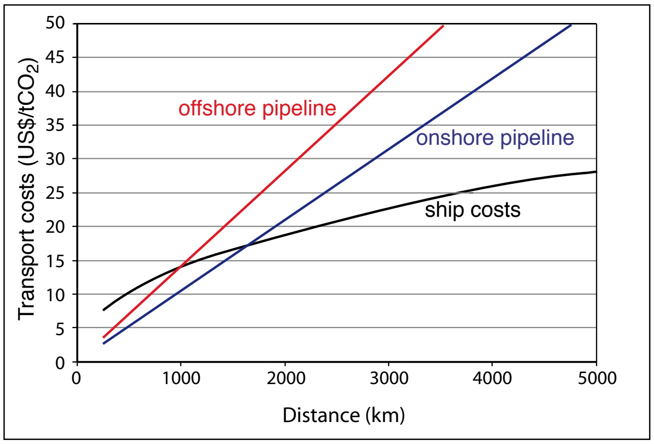

Figure TS.6. Costs, plotted as US$/tCO$_2$ transported against distance, for onshore pipelines, offshore pipelines and ship transport. Pipeline costs are given for a mass flow of 6 MtCO$_2$ yr^{-1}. Ship costs include intermediate storage facilities, harbour fees, fuel costs, and loading and unloading activities. Costs include also additional costs for liquefaction compared to compression.

The costs associated with CO$_2$ compression and liquefaction are accounted for in the capture costs presented earlier. Figure TS.6 compares pipeline and marine transportation costs, and shows the break-even distance. If the marine option is available, it is typically cheaper than pipelines for distances greater than approximately 1000 km and for amounts smaller than a few million tonnes of CO$_2$ per year. In ocean storage the most suitable transport system depends on the injection method: from a stationary floating vessel, a moving ship, or a pipeline from shore.

5. Geological storage

This section examines three types of geological formations that have received extensive consideration for the geological storage of CO$_2$: oil and gas reservoirs, deep saline formations and unminable coal beds (Figure TS.7). In each case, geological storage of CO$_2$ is accomplished by injecting it in dense form into a rock formation below the earth's surface. Porous rock formations that hold or (as in the case of depleted oil and gas reservoirs) have previously held fluids, such as natural gas, oil or brines, are potential candidates for CO$_2$ storage. Suitable storage formations can occur in both onshore and offshore sedimentary basins (natural large-scale depressions in the earth's crust that are filled with sediments). Coal beds also may be used for storage of CO$_2$ (see Figure TS.7) where it is unlikely that the coal will later be mined and provided that permeability is sufficient. The option of storing CO$_2$ in coal beds and enhancing methane production is still in the demonstration phase (see Table TS.1).

Existing CO$_2$ storage projects

Geological storage of CO$_2$ is ongoing in three industrial-scale projects (projects in the order of 1 MtCO$_2$ yr^{-1} or more): the Sleipner project in the North Sea, the Weyburn project in Canada and the In Salah project in Algeria. About 3–4 MtCO$_2$ that would otherwise be released to the atmosphere is captured and stored annually in geological formations. Additional projects are listed in Table TS.5.

In addition to the CCS projects currently in place, 30 MtCO$_2$ is injected annually for EOR, mostly in Texas, USA, where EOR commenced in the early 1970s. Most of this CO$_2$ is obtained from natural CO$_2$ reservoirs found in western regions of the US, with some coming from anthropogenic sources such as natural gas processing. Much of the CO$_2$ injected for EOR is produced with the oil, from which it is separated and then reinjected. At the end of the oil recovery, the CO$_2$ can be retained for the purpose of climate change mitigation, rather than vented to the atmosphere. This is planned for the Weyburn project.

Storage technology and mechanisms

The injection of CO$_2$ in deep geological formations involves many of the same technologies that have been developed in the oil and gas exploration and production industry. Well-drilling technology, injection technology, computer simulation of storage reservoir dynamics and monitoring methods from existing applications are being developed further for design and operation of geological storage. Other underground injection practices also provide relevant operational experience. In particular, natural gas storage, the deep injection of liquid wastes, and acid gas disposal (mixtures of CO$_2$ and H$_2$S) have been conducted in Canada and the U.S. since 1990, also at the megatonne scale.

CO$_2$ storage in hydrocarbon reservoirs or deep saline formations is generally expected to take place at depths below 800 m, where the ambient pressures and temperatures will usually result in CO$_2$ being in a liquid or supercritical state. Under these conditions, the density of CO$_2$ will range from 50 to 80% of the density of water. This is close to the density of some crude oils, resulting in buoyant forces that tend to drive CO$_2$ upwards. Consequently, a well-sealed cap rock over the selected storage reservoir is important to ensure that CO$_2$ remains trapped underground. When injected underground, the CO$_2$ compresses and fills the pore space by partially displacing the fluids that are already present (the 'in situ fluids'). In oil and gas reservoirs, the displacement of in situ fluids by injected CO$_2$ can result in most of the pore volume being available for CO$_2$ storage. In saline formations, estimates of potential storage volume are lower, ranging from as low as a few percent to over 30% of the total rock volume.

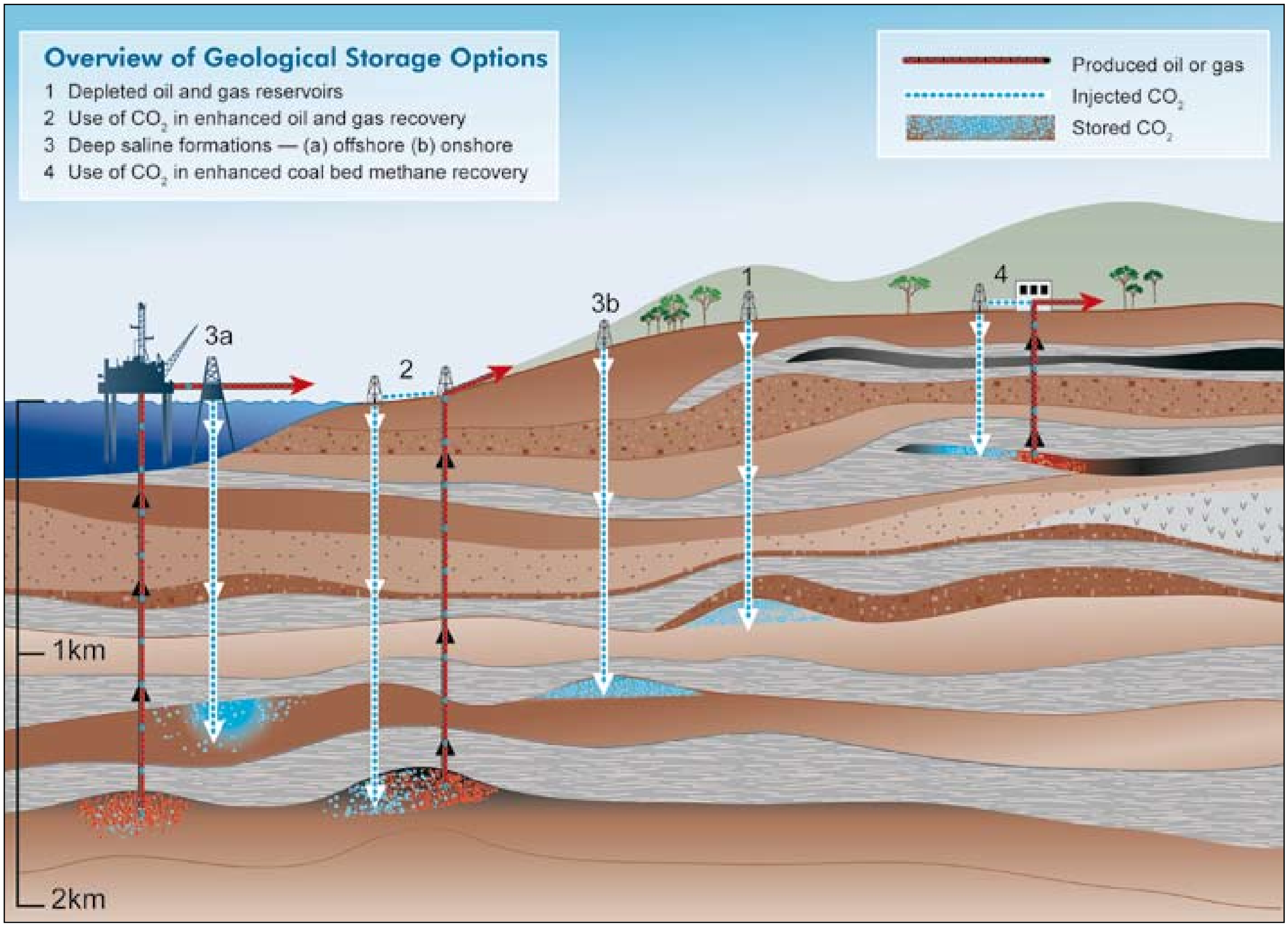

Figure TS.7. Methods for storing CO_2 in deep underground geological formations. Two methods may be combined with the recovery of hydrocarbons: EOR (2) and ECBM (4). See text for explanation of these methods (Courtesy CO2CRC).

Once injected into the storage formation, the fraction retained depends on a combination of physical and geochemical trapping mechanisms. Physical trapping to block upward migration of CO_2 is provided by a layer of shale and clay rock above the storage formation. This impermeable layer is known as the "cap rock". Additional physical trapping can be provided by capillary forces that retain CO_2 in the pore spaces of the formation. In many cases, however, one or more sides of the formation remain open, allowing for lateral migration of CO_2 beneath the cap rock. In these cases, additional mechanisms are important for the long-term entrapment of the injected CO_2.

The mechanism known as geochemical trapping occurs as the CO_2 reacts with the in situ fluids and host rock. First, CO_2 dissolves in the in situ water. Once this occurs (over time scales of hundreds of years to thousands of years), the CO_2-laden water becomes more dense and therefore sinks down into the formation (rather than rising toward the surface). Next, chemical reactions between the dissolved CO_2 and rock minerals form ionic species, so that a fraction of the injected CO_2 will be converted to solid carbonate minerals over millions of years.

Yet another type of trapping occurs when CO_2 is preferentially adsorbed onto coal or organic-rich shales replacing gases such as methane. In these cases, CO_2 will remain trapped as long as pressures and temperatures remain stable. These processes would normally take place at shallower depths than CO_2 storage in hydrocarbon reservoirs and saline formations.

Geographical distribution and capacity of storage sites

As shown earlier in Section 2 (Figure TS.2b), regions with sedimentary basins that are potentially suitable for CO_2 storage exist around the globe, both onshore and offshore. This report focuses on oil and gas reservoirs, deep saline

Table TS.5. Sites where CO_2 storage has been done, is currently in progress or is planned, varying from small pilots to large-scale commercial applications.

Project name	**Country**	**Injection start (year)**	**Approximate average daily injection rate (tCO_2 day^{-1})**	**Total (planned) storage (tCO_2)**	**Storage reservoir type**
Weyburn	Canada	2000	3,000-5,000	20,000,000	EOR
In Salah	Algeria	2004	3,000-4,000	17,000,000	Gas field
Sleipner	Norway	1996	3,000	20,000,000	Saline formation
K12B	Netherlands	2004	100 (1,000 planned for 2006+)	8,000,000	Enhanced gas recovery
Frio	U.S.A	2004	177	1600	Saline formation
Fenn Big Valley	Canada	1998	50	200	ECBM
Qinshui Basin	China	2003	30	150	ECBM
Yubari	Japan	2004	10	200	ECBM
Recopol	Poland	2003	1	10	ECBM
Gorgon (planned)	Australia	~2009	10,000	unknown	Saline formation
Snøhvit (planned)	Norway	2006	2,000	unknown	Saline formation

formations and unminable coal beds. Other possible geological formations or structures (such as basalts, oil or gas shales, salt caverns and abandoned mines) represent niche opportunities, or have been insufficiently studied at this time to assess their potential.

The estimates of the technical potential[6] for different geological storage options are summarized in Table TS.6. The estimates and levels of confidence are based on an assessment of the literature, both of regional bottom-up, and global top-down estimates. No probabilistic approach to assessing capacity estimates exists in the literature, and this would be required to quantify levels of uncertainty reliably. Overall estimates, particularly of the upper limit of the potential, vary widely and involve a high degree of uncertainty, reflecting conflicting methodologies in the literature and the fact that our knowledge of saline formations is quite limited in most parts of the world. For oil and gas reservoirs, better estimates are available which are based on the replacement of hydrocarbon volumes with CO_2 volumes. It should be noted that, with the exception of EOR, these reservoirs will not be available for CO_2 storage until the hydrocarbons are depleted, and that pressure changes and geomechanical effects due to hydrocarbon production in the reservoir may reduce actual capacity.

Another way of looking at storage potential, however, is to ask whether it is likely to be adequate for the amounts of CO_2 that would need to be avoided using CCS under different greenhouse gas stabilization scenarios and assumptions about the deployment of other mitigation options. As discussed later in Section 8, the estimated range of economic potential[7] for CCS over the next century is roughly 200 to 2,000 $GtCO_2$. The lower limits in Table TS.6 suggest that, worldwide, it is virtually certain[8] that there is 200 $GtCO_2$ of geological storage capacity, and likely[9] that there is at least about 2,000 $GtCO_2$.

Site selection criteria and methods

Site characterization, selection and performance prediction are crucial for successful geological storage. Before selecting a site, the geological setting must be characterized to determine if the overlying cap rock will provide an effective seal, if there is a sufficiently voluminous and permeable storage formation, and whether any abandoned or active wells will compromise the integrity of the seal.

Techniques developed for the exploration of oil and gas reservoirs, natural gas storage sites and liquid waste disposal sites are suitable for characterizing geological storage sites for CO_2. Examples include seismic imaging, pumping tests for evaluating storage formations and seals, and cement integrity logs. Computer programmes that model underground CO_2 movement are used to support site characterization and selection activities. These programmes were initially developed for applications such as oil and

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[6] Technical potential is the amount by which it is possible to reduce greenhouse gas emissions by implementing a technology or practice that already has been demonstrated.

[7] Economic potential is the amount of greenhouse gas emissions reductions from a specific option that could be achieved cost-effectively, given prevailing circumstances (the price of CO_2 reductions and costs of other options).

[8] "Virtually certain" is a probability of 99% or more.

[9] "Likely" is a probability of 66 to 90%.

Table TS.6. Storage capacity for several geological storage options. The storage capacity includes storage options that are not economical.

Reservoir type	**Lower estimate of storage capacity ($GtCO_2$)**	**Upper estimate of storage capacity ($GtCO_2$)**
Oil and gas fields	675[a]	900[a]
Unminable coal seams (ECBM)	3-15	200
Deep saline formations	1,000	Uncertain, but possibly 10^4

[a] These numbers would increase by 25% if 'undiscovered' oil and gas fields were included in this assessment.

gas reservoir engineering and groundwater resources investigations. Although they include many of the physical, chemical and geomechanical processes needed to predict both short-term and long-term performance of CO_2 storage, more experience is needed to establish confidence in their effectiveness in predicting long-term performance when adapted for CO_2 storage. Moreover, the availability of good site characterization data is critical for the reliability of models.

Risk assessment and environmental impact

The risks due to leakage from storage of CO_2 in geological reservoirs fall into two broad categories: global risks and local risks. Global risks involve the release of CO_2 that may contribute significantly to climate change if some fraction leaks from the storage formation to the atmosphere. In addition, if CO_2 leaks out of a storage formation, local hazards may exist for humans, ecosystems and groundwater. These are the local risks.

With regard to global risks, based on observations and analysis of current CO_2 storage sites, natural systems, engineering systems and models, the fraction retained in appropriately selected and managed reservoirs is very likely[10] to exceed 99% over 100 years, and is likely to exceed 99% over 1000 years. Similar fractions retained are likely for even longer periods of time, as the risk of leakage is expected to decrease over time as other mechanisms provide additional trapping. The question of whether these fractions retained would be sufficient to make impermanent storage valuable for climate change mitigation is discussed in Section 8.

With regard to local risks, there are two types of scenarios in which leakage may occur. In the first case, injection well failures or leakage up abandoned wells could create a sudden and rapid release of CO_2. This type of release is likely to be detected quickly and stopped using techniques that are available today for containing well blow-outs. Hazards associated with this type of release primarily affect workers in the vicinity of the release at the time it occurs, or those called in to control the blow-out. A concentration of CO_2 greater than 7–10% in air would cause immediate dangers to human life and health. Containing these kinds of releases may take hours to days and the overall amount of CO_2 released is likely to be very small compared to the total amount injected. These types of hazards are managed effectively on a regular basis in the oil and gas industry using engineering and administrative controls.

In the second scenario, leakage could occur through undetected faults, fractures or through leaking wells where the release to the surface is more gradual and diffuse. In this case, hazards primarily affect drinking-water aquifers and ecosystems where CO_2 accumulates in the zone between the surface and the top of the water table. Groundwater can be affected both by CO_2 leaking directly into an aquifer and by brines that enter the aquifer as a result of being displaced by CO_2 during the injection process. There may also be acidification of soils and displacement of oxygen in soils in this scenario. Additionally, if leakage to the atmosphere were to occur in low-lying areas with little wind, or in sumps and basements overlying these diffuse leaks, humans and animals would be harmed if a leak were to go undetected. Humans would be less affected by leakage from offshore storage locations than from onshore storage locations. Leakage routes can be identified by several techniques and by characterization of the reservoir. Figure TS.8 shows some of the potential leakage paths for a saline formation. When the potential leakage routes are known, the monitoring and remediation strategy can be adapted to address the potential leakage.

Careful storage system design and siting, together with methods for early detection of leakage (preferably long before CO_2 reaches the land surface), are effective ways of reducing hazards associated with diffuse leakage. The available monitoring methods are promising, but more experience is needed to establish detection levels and resolution. Once leakages are detected, some remediation techniques are available to stop or control them. Depending on the type of leakage, these techniques could involve standard well repair techniques, or the extraction of CO_2 by intercepting its leak into a shallow groundwater aquifer (see Figure TS.8).

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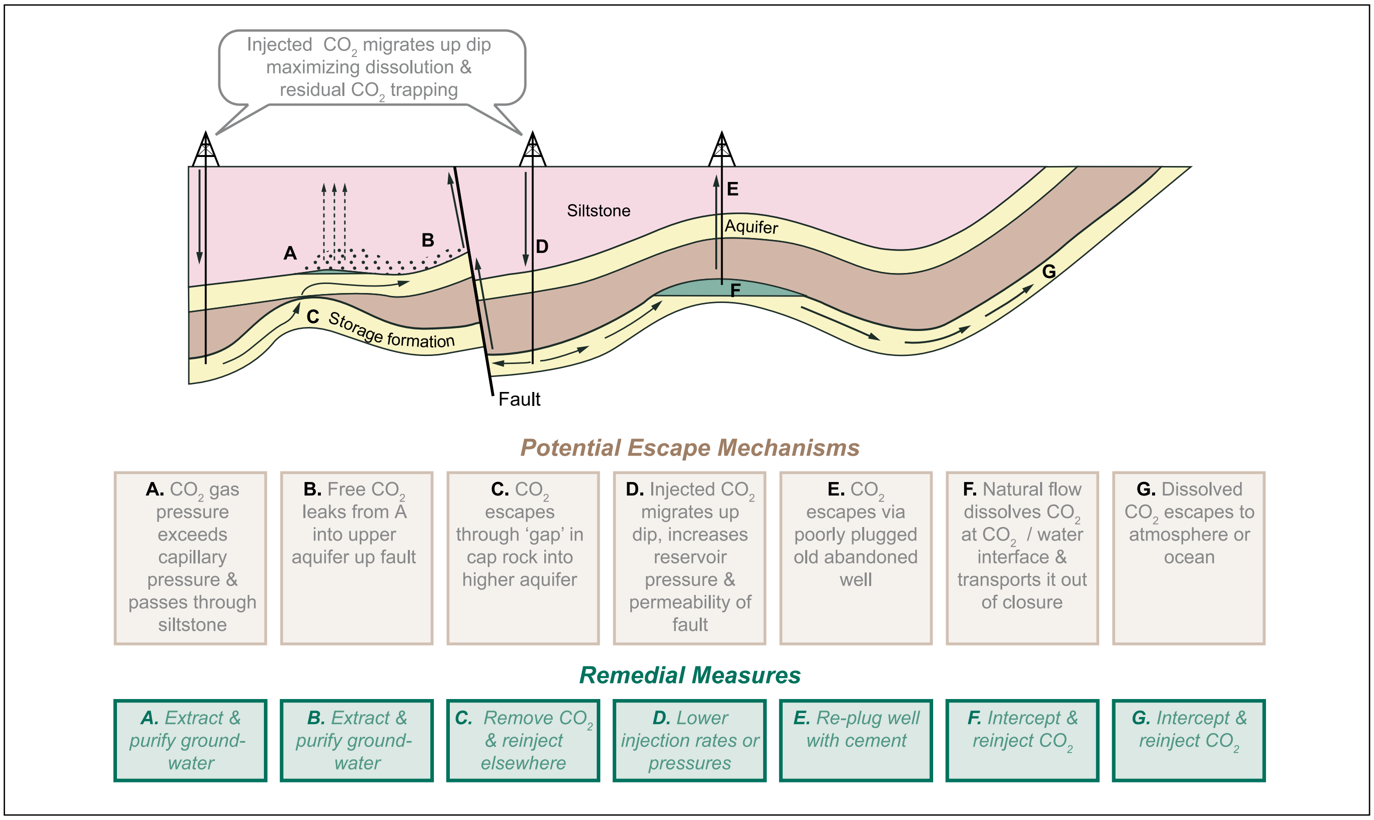
[10] "Very likely" is a probability of 90 to 99%.



Potential Escape Mechanisms

A. CO_2 gas pressure exceeds capillary pressure & passes through siltstone

B. Free CO_2 leaks from A into upper aquifer up fault

C. CO_2 escapes through 'gap' in cap rock into higher aquifer

D. Injected CO_2 migrates up dip, increases reservoir pressure & permeability of fault

E. CO_2 escapes via poorly plugged old abandoned well

F. Natural flow dissolves CO_2 at CO_2 / water interface & transports it out of closure

G. Dissolved CO_2 escapes to atmosphere or ocean

Remedial Measures

A. *Extract & purify ground-water*

B. *Extract & purify ground-water*

C. *Remove CO_2 & reinject elsewhere*

D. *Lower injection rates or pressures*

E. *Re-plug well with cement*

F. *Intercept & reinject CO_2*

G. *Intercept & reinject CO_2*

Figure TS.8. Potential leakage routes and remediation techniques for CO_2 injected into saline formations. The remediation technique would depend on the potential leakage routes identified in a reservoir (Courtesy CO2CRC).

Techniques to remove CO_2 from soils and groundwater are also available, but they are likely to be costly. Experience will be needed to demonstrate the effectiveness, and ascertain the costs, of these techniques for use in CO_2 storage.

Monitoring and verification

Monitoring is a very important part of the overall risk management strategy for geological storage projects. Standard procedures or protocols have not been developed yet but they are expected to evolve as technology improves, depending on local risks and regulations. However, it is expected that some parameters such as injection rate and injection well pressure will be measured routinely. Repeated seismic surveys have been shown to be useful for tracking the underground migration of CO_2. Newer techniques such as gravity and electrical measurements may also be useful. The sampling of groundwater and the soil between the surface and water table may be useful for directly detecting CO_2 leakage. CO_2 sensors with alarms can be located at the injection wells for ensuring worker safety and to detect leakage. Surface-based techniques may also be used for detecting and quantifying surface releases. High-quality baseline data improve the reliability and resolution of all measurements and will be essential for detecting small rates of leakage.

Since all of these monitoring techniques have been adapted from other applications, they need to be tested and assessed with regard to reliability, resolution and sensitivity in the context of geological storage. All of the existing industrial-scale projects and pilot projects have programmes to develop and test these and other monitoring techniques. Methods also may be necessary or desirable to monitor the amount of CO_2 stored underground in the context of emission reporting and monitoring requirements in the UNFCCC (see Section 9). Given the long-term nature of CO_2 storage, site monitoring may be required for very long periods.

Legal issues

At present, few countries have specifically developed legal and regulatory frameworks for onshore CO_2 storage. Relevant legislation include petroleum-related legislation, drinking-water legislation and mining regulations. In many cases, there are laws applying to some, if not most, of the issues related to CO_2 storage. Specifically, long-term liability issues, such as global issues associated with the leakage of CO_2 to the atmosphere, as well as local concerns about environmental impact, have not yet been addressed. Monitoring and verification regimes and risks of leakage may play an important role in determining liability, and vice-versa. There are also considerations such as the longevity of institutions, ongoing monitoring and transferability of institutional knowledge. The long-term perspective is essential to a legal framework for CCS as storage times extend over many generations as does the climate change problem. In some countries, notably the US, the property rights of all those affected must be considered in legal terms as pore space is owned by surface property owners.

According to the general principles of customary international law, States can exercise their sovereignty in their territories and could therefore engage in activities such as the storage of CO_2 (both geological and ocean) in those areas under their jurisdiction. However, if storage has a transboundary impact, States have the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction.

Currently, there are several treaties (notably the UN Convention on the Law of the Sea, and the London[11] and OSPAR[12] Conventions) that could apply to the offshore injection of CO_2 into marine environments (both into the ocean and the geological sub-seabed). All these treaties have been drafted without specific consideration of CO_2 storage. An assessment undertaken by the Jurists and Linguists Group to the OSPAR Convention (relating to the northeast Atlantic region), for example, found that, depending on the method and purpose of injection, CO_2 injection into the geological sub-seabed and the ocean could be compatible with the treaty in some cases, such as when the CO_2 is transported via a pipeline from land. A similar assessment is now being conducted by Parties to the London Convention. Furthermore, papers by legal commentators have concluded that CO_2 captured from an oil or natural gas extraction operation and stored offshore in a geological formation (like the Sleipner operation) would not be considered ‘dumping’ under, and would not therefore be prohibited by, the London Convention.

Public perception

Assessing public perception of CCS is challenging because of the relatively technical and “remote” nature of this issue at the present time. Results of the very few studies conducted to date about the public perception of CCS indicate that the public is generally not well informed about CCS. If information is given alongside information about other climate change mitigation options, the handful of studies carried out so far indicate that CCS is generally regarded as less favourable than other options, such as improvements in energy efficiency and the use of non-fossil energy sources. Acceptance of CCS, where it occurs, is characterized as “reluctant” rather than “enthusiastic”. In some cases, this reflects the perception that CCS might be required because of a failure to reduce CO_2 emissions in other ways. There are indications that geological storage could be viewed favourably if it is adopted in conjunction with more desirable measures. Although public perception is likely to change in the future, the limited research to date indicates that at least two conditions may have to be met before CO_2 capture and storage is considered by the public as a credible technology, alongside other better known options: (1) anthropogenic global climate change has to be regarded as a relatively serious problem; (2) there must be acceptance of the need for large reductions in CO_2 emissions to reduce the threat of global climate change.

Cost of geological storage

The technologies and equipment used for geological storage are widely used in the oil and gas industries so cost estimates for this option have a relatively high degree of confidence for storage capacity in the lower range of technical potential. However, there is a significant range and variability of costs due to site-specific factors such as onshore versus offshore, reservoir depth and geological characteristics of the storage formation (e.g., permeability and formation thickness).

Representative estimates of the cost for storage in saline formations and depleted oil and gas fields are typically between 0.5–8 US\$/tCO_2 injected. Monitoring costs of 0.1–0.3 US\$/tCO_2 are additional. The lowest storage costs are for onshore, shallow, high permeability reservoirs, and/or storage sites where wells and infrastructure from existing oil and gas fields may be re-used.

When storage is combined with EOR, ECBM or (potentially) Enhanced Gas Recovery (EGR), the economic value of CO_2 can reduce the total cost of CCS. Based on data and oil prices prior to 2003, enhanced oil production for onshore EOR with CO_2 storage could yield net benefits of 10–16 US\$/tCO_2 (37–59 US\$/tC) (including the costs of geological storage). For EGR and ECBM, which are still under development, there is no reliable cost information based on actual experience. In all cases, however, the economic benefit of enhanced production

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[11] Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972), and its London Protocol (1996), which has not yet entered into force.

[12] Convention for the Protection of the Marine Environment of the North-East Atlantic, which was adopted in Paris (1992). OSPAR is an abbreviation of Oslo-Paris.

depends strongly on oil and gas prices. In this regard, the literature basis for this report does not take into account the rise in world oil and gas prices since 2003 and assumes oil prices of 15–20 US$ per barrel. Should higher prices be sustained over the life of a CCS project, the economic value of CO_2 could be higher than that reported here.

6. Ocean storage

A potential CO_2 storage option is to inject captured CO_2 directly into the deep ocean (at depths greater than 1,000 m), where most of it would be isolated from the atmosphere for centuries. This can be achieved by transporting CO_2 via pipelines or ships to an ocean storage site, where it is injected into the water column of the ocean or at the sea floor. The dissolved and dispersed CO_2 would subsequently become part of the global carbon cycle. Figure TS.9 shows some of the main methods that could be employed. Ocean storage has not yet been deployed or demonstrated at a pilot scale, and is still in the research phase. However, there have been small-scale field experiments and 25 years of theoretical, laboratory and modelling studies of intentional ocean storage of CO_2.

Storage mechanisms and technology

Oceans cover over 70% of the earth's surface and their average depth is 3,800 m. Because carbon dioxide is soluble in water, there are natural exchanges of CO_2 between the atmosphere and waters at the ocean surface that occur until equilibrium is reached. If the atmospheric concentration of CO_2 increases, the ocean gradually takes up additional CO_2. In this way, the oceans have taken up about 500 $GtCO_2$ (140 GtC) of the total 1,300 $GtCO_2$ (350 GtC) of anthropogenic emissions released to the atmosphere over the past 200 years. As a result of the increased atmospheric CO_2 concentrations from human activities relative to pre-industrial levels, the oceans are currently taking up CO_2 at a rate of about 7 $GtCO_2$ yr^{-1} (2 GtC yr^{-1}).

Most of this carbon dioxide now resides in the upper ocean and thus far has resulted in a decrease in *p*H of about 0.1 at the ocean surface because of the acidic nature of CO_2 in water. To date, however, there has been virtually no change in *p*H in the deep ocean. Models predict that over the next several centuries the oceans will eventually take up most of the CO_2 released to the atmosphere as CO_2 is dissolved at the ocean surface and subsequently mixed with deep ocean waters.

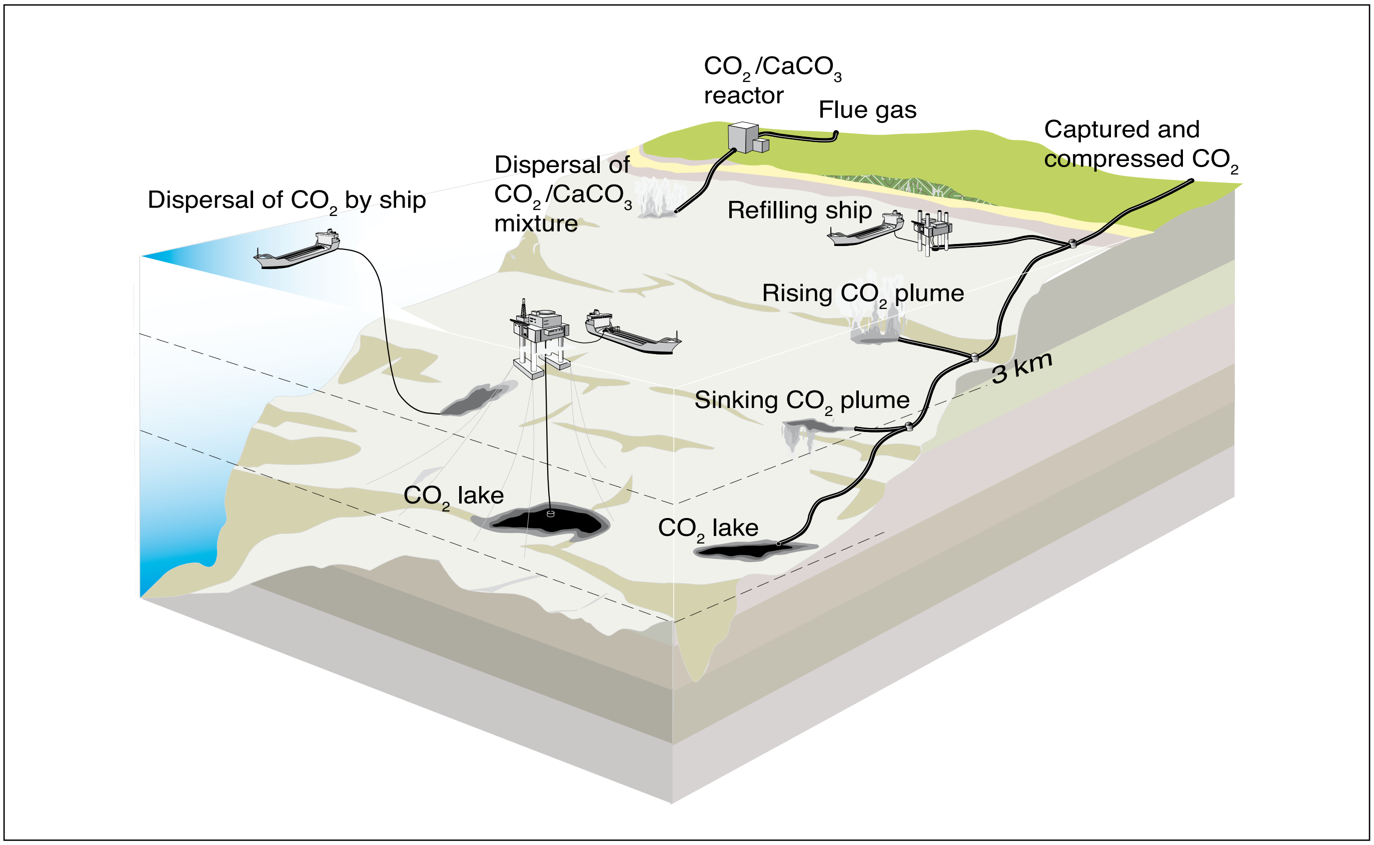

Figure TS.9. Methods of ocean storage.

There is no practical physical limit to the amount of anthropogenic CO_2 that could be stored in the ocean. However, on a millennial time scale, the amount stored will depend on oceanic equilibration with the atmosphere. Stabilizing atmospheric CO_2 concentrations between 350 ppmv and 1000 ppmv would imply that between 2,000 and 12,000 $GtCO_2$ would eventually reside in the ocean if there is no intentional CO_2 injection. This range therefore represents the upper limit for the capacity of the ocean to store CO_2 through active injection. The capacity would also be affected by environmental factors, such as a maximum allowable *p*H change.

Analysis of ocean observations and models both indicate that injected CO_2 will be isolated from the atmosphere for at least several hundreds of years, and that the fraction retained tends to be higher with deeper injection (see Table TS.7). Ideas for increasing the fraction retained include forming solid CO_2 hydrates and/or liquid CO_2 lakes on the sea floor, and dissolving alkaline minerals such as limestone to neutralize the acidic CO_2. Dissolving mineral carbonates, if practical, could extend the storage time scale to roughly 10,000 years, while minimizing changes in ocean *p*H and CO_2 partial pressure. However, large amounts of limestone and energy for materials handling would be required for this approach (roughly the same order of magnitude as the amounts per tonne of CO_2 injected that are needed for mineral carbonation; see Section 7).

Ecological and environmental impacts and risks

The injection of a few $GtCO_2$ would produce a measurable change in ocean chemistry in the region of injection, whereas the injection of hundreds of $GtCO_2$ would produce larger changes in the region of injection and eventually produce measurable changes over the entire ocean volume. Model simulations that assume a release from seven locations at 3,000 m depth and ocean storage providing 10% of the mitigation effort for stabilization at 550 ppmv CO_2 projected acidity changes (*p*H changes) of more than 0.4 over approximately 1% of the ocean volume. By comparison, in a 550 ppmv stabilization case without ocean storage, a *p*H change of more than 0.25 at the ocean surface was estimated due to equilibration with the elevated CO_2 concentrations in the atmosphere. In either case, a *p*H change of 0.2 to 0.4 is significantly greater than pre-industrial variations in ocean acidity. Over centuries, ocean mixing will result in the loss of isolation of injected CO_2. As more CO_2 reaches the ocean surface waters, releases into the atmosphere would occur gradually from large regions of the ocean. There are no known mechanisms for sudden or catastrophic release of injected CO_2 from the ocean into the atmosphere.

Experiments show that adding CO_2 can harm marine organisms. Effects of elevated CO_2 levels have mostly been studied on time scales up to several months in individual organisms that live near the ocean surface. Observed phenomena include reduced rates of calcification, reproduction, growth, circulatory oxygen supply and mobility, as well as increased mortality over time. In some organisms these effects are seen in response to small additions of CO_2. Immediate mortality is expected close to injection points or CO_2 lakes. The chronic effects of direct CO_2 injection into the ocean on ocean organisms or ecosystems over large ocean areas and long time scales have not yet been studied.

No controlled ecosystem experiments have been performed in the deep ocean, so only a preliminary assessment of potential ecosystem effects can be given. It is expected that ecosystem consequences will increase with increasing CO_2 concentrations and decreasing *p*H, but the nature of such consequences is currently not understood, and no environmental criteria have as yet been identified to avoid adverse effects. At present, it is also unclear how or whether species and ecosystems would adapt to the sustained chemical changes.

Costs of ocean storage

Although there is no experience with ocean storage, some attempts have been made to estimate the costs of CO_2 storage projects that release CO_2 on the sea floor or in the deep ocean. The costs of CO_2 capture and transport to the shoreline (e.g

Table TS.7. Fraction of CO_2 retained for ocean storage as simulated by seven ocean models for 100 years of continuous injection at three different depths starting in the year 2000.

	Injection depth		
Year	**800 m**	**1500 m**	**3000 m**
2100	0.78 ± 0.06	0.91 ± 0.05	0.99 ± 0.01
2200	0.50 ± 0.06	0.74 ± 0.07	0.94 ± 0.06
2300	0.36 ± 0.06	0.60 ± 0.08	0.87 ± 0.10
2400	0.28 ± 0.07	0.49 ± 0.09	0.79 ± 0.12
2500	0.23 ± 0.07	0.42 ± 0.09	0.71 ± 0.14

Table TS.8. Costs for ocean storage at depths deeper than 3,000 m.

Ocean storage method	Costs (US$/tCO$_2$ net injected)	
	100 km offshore	500 km offshore
Fixed pipeline	6	31
Moving ship/platform[a]	12-14	13-16

[a] The costs for the moving ship option are for injection depths of 2,000-2,500 m.

via pipelines) are not included in the cost of ocean storage. However, the costs of offshore pipelines or ships, plus any additional energy costs, are included in the ocean storage cost. The costs of ocean storage are summarized in Table TS.8. These numbers indicate that, for short distances, the fixed pipeline option would be cheaper. For larger distances, either the moving ship or the transport by ship to a platform with subsequent injection would be more attractive.

Legal aspects and public perception

The global and regional treaties on the law of the sea and marine environment, such as the OSPAR and the London Convention discussed earlier in Section 5 for geological storage sites, also affect ocean storage, as they concern the 'maritime area'. Both Conventions distinguish between the storage method employed and the purpose of storage to determine the legal status of ocean storage of CO_2. As yet, however, no decision has been made about the legal status of intentional ocean storage.

The very small number of public perception studies that have looked at the ocean storage of CO_2 indicate that there is very little public awareness or knowledge of this subject. In the few studies conducted thus far, however, the public has expressed greater reservations about ocean storage than geological storage. These studies also indicate that the perception of ocean storage changed when more information was provided; in one study this led to increased acceptance of ocean storage, while in another study it led to less acceptance. The literature also notes that 'significant opposition' developed around a proposed CO_2 release experiment in the Pacific Ocean.

7. Mineral carbonation and industrial uses

This section deals with two rather different options for CO_2 storage. The first is mineral carbonation, which involves converting CO_2 to solid inorganic carbonates using chemical reactions. The second option is the industrial use of CO_2, either directly or as feedstock for production of various carbon-containing chemicals.

Mineral carbonation: technology, impacts and costs

Mineral carbonation refers to the fixation of CO_2 using alkaline and alkaline-earth oxides, such as magnesium oxide (MgO) and calcium oxide (CaO), which are present in naturally occurring silicate rocks such as serpentine and olivine. Chemical reactions between these materials and CO_2 produces compounds such as magnesium carbonate ($MgCO_3$) and calcium carbonate ($CaCO_3$, commonly known as limestone). The quantity of metal oxides in the silicate rocks that can be found in the earth's crust exceeds the amounts needed to fix all the CO_2 that would be produced by the combustion of all available fossil fuel reserves. These oxides are also present in small quantities in some industrial wastes, such as stainless steel slags and ashes. Mineral carbonation produces silica and carbonates that are stable over long time scales and can therefore be disposed of in areas such as silicate mines, or re-used for construction purposes (see Figure TS.10), although such re-use is likely to be small relative to the amounts produced. After carbonation, CO_2 would not be released to the atmosphere. As a consequence, there would be little need to monitor the disposal sites and the associated risks would be very low. The storage potential is difficult to estimate at this early phase of development. It would be limited by the fraction of silicate reserves that can be technically exploited, by environmental issues such as the volume of product disposal, and by legal and societal constraints at the storage location.

The process of mineral carbonation occurs naturally, where it is known as 'weathering'. In nature, the process occurs very slowly; it must therefore be accelerated considerably to be a viable storage method for CO_2 captured from anthropogenic sources. Research in the field of mineral carbonation therefore focuses on finding process routes that can achieve reaction rates viable for industrial purposes and make the reaction more energy-efficient. Mineral carbonation technology using natural silicates is in the research phase but some processes using industrial wastes are in the demonstration phase.

A commercial process would require mining, crushing and milling of the mineral-bearing ores and their transport to a processing plant receiving a concentrated CO_2 stream from a capture plant (see Figure TS.10). The carbonation process

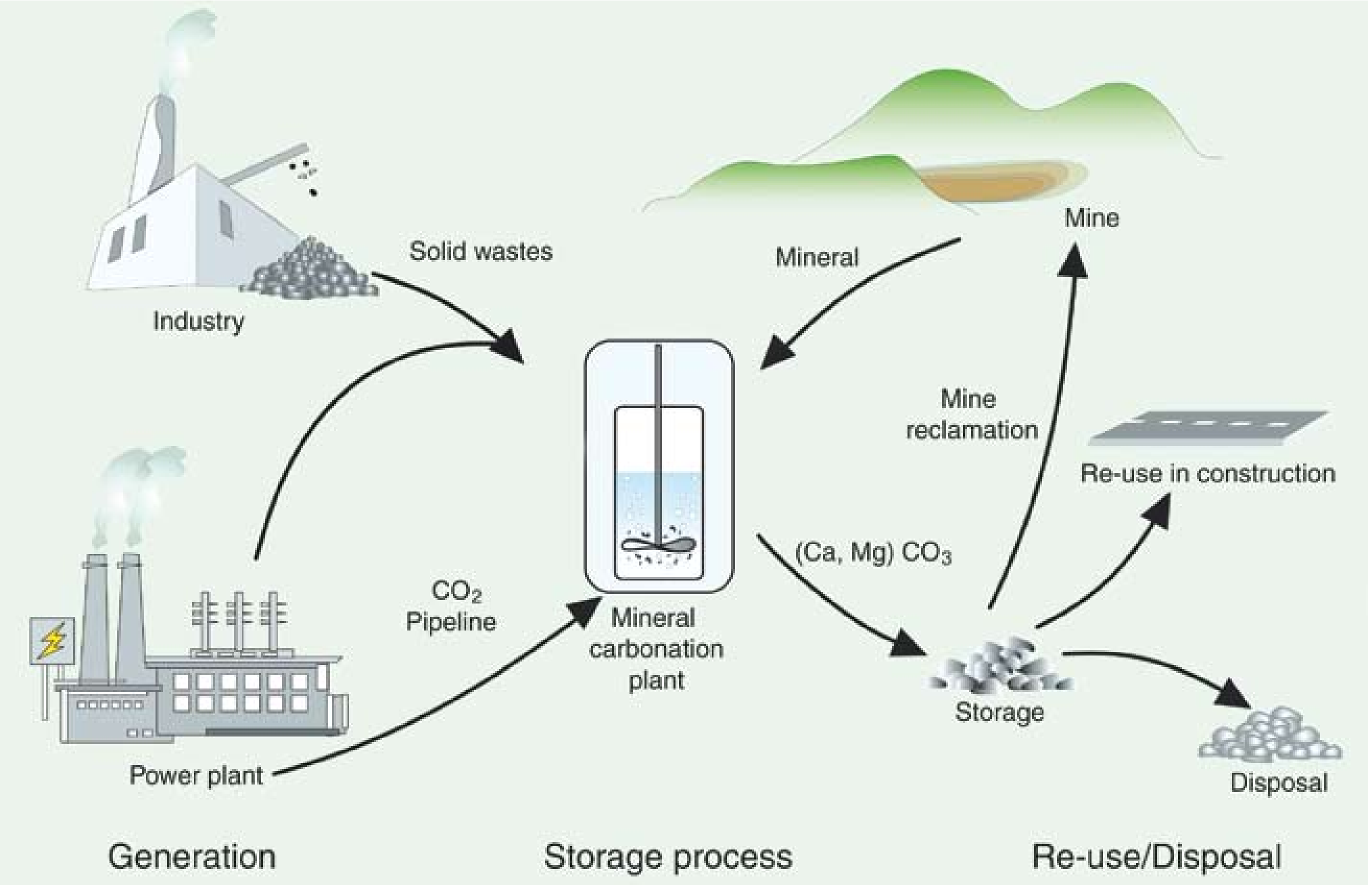

Figure TS.10. Material fluxes and process steps associated with the mineral carbonation of silicate rocks or industrial residues (Courtesy ECN).

energy required would be 30 to 50% of the capture plant output. Considering the additional energy requirements for the capture of CO_2, a CCS system with mineral carbonation would require 60 to 180% more energy input per kilowatt-hour than a reference electricity plant without capture or mineral carbonation. These energy requirements raise the cost per tonne of CO_2 avoided for the overall system significantly (see Section 8). The best case studied so far is the wet carbonation of natural silicate olivine. The estimated cost of this process is approximately 50–100 US$/t$CO_2$ net mineralized (in addition to CO_2 capture and transport costs, but taking into account the additional energy requirements). The mineral carbonation process would require 1.6 to 3.7 tonnes of silicates per tonne of CO_2 to be mined, and produce 2.6 to 4.7 tonnes of materials to be disposed per tonne of CO_2 stored as carbonates. This would therefore be a large operation, with an environmental impact similar to that of current large-scale surface mining operations. Serpentine also often contains chrysotile, a natural form of asbestos. Its presence therefore demands monitoring and mitigation measures of the kind available in the mining industry. On the other hand, the products of mineral carbonation are chrysotile-free, since this is the most reactive component of the rock and therefore the first substance converted to carbonates.

A number of issues still need to be clarified before any estimates of the storage potential of mineral carbonation can be given. The issues include assessments of the technical feasibility and corresponding energy requirements at large scales, but also the fraction of silicate reserves that can be technically and economically exploited for CO_2 storage. The environmental impact of mining, waste disposal and product storage could also limit potential. The extent to which mineral carbonation may be used cannot be determined at this time, since it depends on the unknown amount of silicate reserves that can be technically exploited, and environmental issuessuch as those noted above.

Industrial uses

Industrial uses of CO_2 include chemical and biological processes where CO_2 is a reactant, such as those used in urea and methanol production, as well as various technological applications that use CO_2 directly, for example in the horticulture industry, refrigeration, food packaging, welding, beverages and fire extinguishers. Currently, CO_2 is used at a rate of approximately 120 $MtCO_2$ per year (30 MtC yr^{-1}) worldwide, excluding use for EOR (discussed in Section 5). Most (two thirds of the total) is used to produce urea, which is used in the manufacture of fertilizers and other products. Some of the CO_2 is extracted from natural wells, and some originates from industrial sources – mainly high-concentration sources such as ammonia and hydrogen production plants – that capture CO_2 as part of the production process.

Industrial uses of CO_2 can, in principle, contribute to keeping CO_2 out of the atmosphere by storing it in the "carbon chemical pool" (i.e., the stock of carbon-bearing manufactured products). However, as a measure for mitigating climate change, this option is meaningful only if the quantity and duration of CO_2 stored are significant, and if there is a real net reduction of CO_2 emissions. The typical lifetime of most of the CO_2 currently used by industrial processes has storage times of only days to months. The stored carbon is then degraded to CO_2 and again emitted to the atmosphere. Such short time scales do not contribute meaningfully to climate change mitigation. In addition, the total industrial use figure of 120 $MtCO_2$ yr^{-1} is small compared to emissions from major anthropogenic sources (see Table TS.2). While some industrial processes store a small proportion of CO_2 (totalling roughly 20 $MtCO_2$ yr^{-1}) for up to several decades, the total amount of long-term (century-scale) storage is presently in the order of 1 $MtCO_2$ yr^{-1} or less, with no prospects for major increases.

Another important question is whether industrial uses of CO_2 can result in an overall net reduction of CO_2 emissions by substitution for other industrial processes or products. This can be evaluated correctly only by considering proper system boundaries for the energy and material balances of the CO_2 utilization processes, and by carrying out a detailed life-cycle analysis of the proposed use of CO_2. The literature in this area is limited but it shows that precise figures are difficult to estimate and that in many cases industrial uses could lead to an increase in overall emissions rather than a net reduction. In view of the low fraction of CO_2 retained, the small volumes used and the possibility that substitution may lead to increases in CO_2 emissions, it can be concluded that the contribution of industrial uses of captured CO_2 to climate change mitigation is expected to be small.

8. Costs and economic potential

The stringency of future requirements for the control of greenhouse gas emissions and the expected costs of CCS systems will determine, to a large extent, the future deployment of CCS technologies relative to other greenhouse gas mitigation options. This section first summarizes the overall cost of CCS for the main options and process applications considered in previous sections. As used in this summary and the report, "costs" refer only to market prices but do not include external costs such as environmental damages and broader societal costs that may be associated with the use of CCS. To date, little has been done to assess and quantify such external costs. Finally CCS is examined in the context of alternative options for global greenhouse gas reductions.

Cost of CCS systems

As noted earlier, there is still relatively little experience with the combination of CO_2 capture, transport and storage in a fully integrated CCS system. And while some CCS components are already deployed in mature markets for certain industrial applications, CCS has still not been used in large-scale power plants (the application with most potential).

The literature reports a fairly wide range of costs for CCS components (see Sections 3–7). The range is due primarily to the variability of site-specific factors, especially the design, operating and financing characteristics of the power plants or industrial facilities in which CCS is used; the type and costs of fuel used; the required distances, terrains and quantities involved in CO_2 transport; and the type and characteristics of the CO_2 storage. In addition, uncertainty still remains about the performance and cost of current and future CCS technology components and integrated systems. The literature reflects a widely-held belief, however, that the cost of building and operating CO_2 capture systems will decline over time as a result of learning-by-doing (from technology deployment) and sustained R&D. Historical evidence also suggests that costs for first-of-a-kind capture plants could exceed current estimates before costs subsequently decline. In most CCS systems, the cost of capture (including compression) is the largest cost component. Costs of electricity and fuel vary considerably from country to country, and these factors also influence the economic viability of CCS options.

Table TS.9 summarizes the costs of CO_2 capture, transport and storage reported in Sections 3 to 7. Monitoring costs are also reflected. In Table TS.10, the component costs are combined to show the total costs of CCS and electricity generation for three power systems with pipeline transport and two geological storage options.

For the plants with geological storage and no EOR credit, the cost of CCS ranges from 0.02–0.05 US$/kWh for PC plants and 0.01–0.03 US$/kWh for NGCC plants (both employing post-combustion capture). For IGCC plants (using pre-combustion capture), the CCS cost ranges from 0.01–0.03 US$/kWh relative to a similar plant without CCS. For all electricity systems, the cost of CCS can be reduced by about 0.01–0.02 US$/kWh when using EOR with CO_2 storage because the EOR revenues partly compensate for the CCS costs. The largest cost reductions are seen for coal-based plants, which capture the largest amounts of CO_2. In a few cases, the low end of the CCS cost range can be negative,

Table TS.9. 2002 Cost ranges for the components of a CCS system as applied to a given type of power plant or industrial source. The costs of the separate components cannot simply be summed to calculate the costs of the whole CCS system in US\$/CO_2 avoided. All numbers are representative of the costs for large-scale, new installations, with natural gas prices assumed to be 2.8-4.4 US\$ GJ^{-1} and coal prices 1-1.5 US\$ GJ^{-1}.

CCS system components	Cost range	Remarks
Capture from a coal- or gas-fired power plant	15-75 US\$/tCO_2 net captured	Net costs of captured CO_2, compared to the same plant without capture.
Capture from hydrogen and ammonia production or gas processing	5-55 US\$/tCO_2 net captured	Applies to high-purity sources requiring simple drying and compression.
Capture from other industrial sources	25-115 US\$/tCO_2 net captured	Range reflects use of a number of different technologies and fuels.
Transportation	1-8 US\$/tCO_2 transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) MtCO_2 yr^{-1}.
Geological storage[a]	0.5-8 US\$/tCO_2 net injected	Excluding potential revenues from EOR or ECBM.
Geological storage: monitoring and verification	0.1-0.3 US\$/tCO_2 injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements.
Ocean storage	5-30 US\$/tCO_2 net injected	Including offshore transportation of 100-500 km, excluding monitoring and verification.
Mineral carbonation	50-100 US\$/tCO_2 net mineralized	Range for the best case studied. Includes additional energy use for carbonation.

[a] Over the long term, there may be additional costs for remediation and liabilities.

indicating that the assumed credit for EOR over the life of the plant is greater than the lowest reported cost of CO_2 capture for that system. This might also apply in a few instances of low-cost capture from industrial processes.

In addition to fossil fuel-based energy conversion processes, CO_2 could also be captured in power plants fueled with biomass, or fossil-fuel plants with biomass co-firing. At present, biomass plants are small in scale (less than 100 MW_e). This means that the resulting costs of production with and without CCS are relatively high compared to fossil alternatives. Full CCS costs for biomass could amount to 110 US\$/tCO_2 avoided. Applying CCS to biomass-fuelled or co-fired conversion facilities would lead to lower or negative[13] CO_2 emissions, which could reduce the costs for this option, depending on the market value of CO_2 emission reductions. Similarly, CO_2 could be captured in biomass-fueled H_2 plants. The cost is reported to be 22–25 US\$/tCO_2 (80–92 US\$/tC) avoided in a plant producing 1 million Nm^3 day^{-1} of H_2, and corresponds to an increase in the H_2 product costs of about 2.7 US\$ GJ^{-1}. Significantly larger biomass plants could potentially benefit from economies of scale, bringing down costs of the CCS systems to levels broadly similar to coal plants. However, to date, there has been little experience with large-scale biomass plants, so their feasibility has not been proven yet, and costs and potential are difficult to estimate.

The cost of CCS has not been studied in the same depth for non-power applications. Because these sources are very diverse in terms of CO_2 concentration and gas stream pressure, the available cost studies show a very broad range. The lowest costs were found for processes that already separate CO_2 as part of the production process, such as hydrogen production (the cost of capture for hydrogen production was reported earlier in Table TS.4). The full CCS cost, including transport and storage, raises the cost of hydrogen production by 0.4 to 4.4 US\$ GJ^{-1} in the case of geological storage, and by -2.0 to 2.8 US\$ GJ^{-1} in the case of EOR, based on the same cost assumptions as for Table TS.10.

Cost of CO_2 avoided

Table TS.10 also shows the ranges of costs for 'CO_2 avoided'. CCS energy requirements push up the amount of fuel input (and therefore CO_2 emissions) per unit of net power output. As a result, the amount of CO_2 produced per unit of product (a kWh of electricity) is greater for the power plant with CCS than the reference plant, as shown in Figure TS.11. To determine the CO_2 reductions one can attribute to CCS, one needs to compare CO_2 emissions per kWh of the plant with capture to that of a reference plant without capture. The difference is referred to as the 'avoided emissions'.

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[13] If for example the biomass is harvested at an unsustainable rate (that is, faster than the annual re-growth), the net CO_2 emissions of the activity might not be negative.

Table TS.10. Range of total costs for CO_2 capture, transport and geological storage based on current technology for new power plants using bituminous coal or natural gas

Power plant performance and cost parameters[a]		Pulverized coal power plant	Natural gas combined cycle power plant	Integrated coal gasification combined cycle power plant
Reference plant without CCS				
Cost of electricity (US$/kWh)		0.043-0.052	0.031-0.050	0.041-0.061
Power plant with capture				
Increased fuel requirement (%)		24-40	11-22	14-25
CO_2 captured (kg/kWh)		0.82-0.97	0.36-0.41	0.67-0.94
CO_2 avoided (kg/kWh)		0.62-0.70	0.30-0.32	0.59-0.73
% CO_2 avoided		81-88	83-88	81-91
Power plant with capture and geological storage[b]				
Cost of electricity (US$/kWh)		0.063-0.099	0.043-0.077	0.055-0.091
Cost of CCS (US$/kWh)		0.019-0.047	0.012-0.029	0.010-0.032
% increase in cost of electricity		43-91	37-85	21-78
Mitigation cost	(US$/t$CO_2$ avoided)	30-71	38-91	14-53
	(US$/tC avoided)	110-260	140-330	51-200
Power plant with capture and enhanced oil recovery[c]				
Cost of electricity (US$/kWh)		0.049-0.081	0.037-0.070	0.040-0.075
Cost of CCS (US$/kWh)		0.005-0.029	0.006-0.022	(-0.005)-0.019
% increase in cost of electricity		12-57	19-63	(-10)-46
Mitigation cost	(US$/t$CO_2$ avoided)	9-44	19-68	(-7)-31
	(US$/tC avoided)	31-160	71-250	(-25)-120

[a] All changes are relative to a similar (reference) plant without CCS. See Table TS.3 for details of assumptions underlying reported cost ranges.

[b] Capture costs based on ranges from Table TS.3; transport costs range from 0-5 US$/t$CO_2$; geological storage cost ranges from 0.6-8.3 US$/t$CO_2$.

[c] Same capture and transport costs as above; Net storage costs for EOR range from -10 to -16 US$/t$CO_2$ (based on pre-2003 oil prices of 15-20 US$ per barrel).

Introducing CCS to power plants may influence the decision about which type of plant to install and which fuel to use. In some situations therefore, it can be useful to calculate a cost per tonne of CO_2 avoided based on a reference plant different from the CCS plant. Table TS.10 displays the cost and emission factors for the three reference plants and the corresponding CCS plants for the case of geological storage. Table TS.11 summarizes the range of estimated costs for different combinations of CCS plants and the lowest-cost reference plants of potential interest. It shows, for instance, that where a PC plant is planned initially, using CCS in that plant may lead to a higher CO_2 avoidance cost than if an NGCC plant with CCS is selected, provided natural gas is available. Another option with lower avoidance cost could be to build an IGCC plant with capture instead of equipping a PC plant with capture.

Economic potential of CCS for climate change mitigation

Assessments of the economic potential of CCS are based on energy and economic models that study future CCS deployment and costs in the context of scenarios that achieve economically efficient, least-cost paths to the stabilization of atmospheric CO_2 concentrations.

While there are significant uncertainties in the quantitative results from these models (see discussion below), all models indicate that CCS systems are unlikely to be deployed on a large scale in the absence of an explicit policy that substantially limits greenhouse gas emissions to the atmosphere. With greenhouse gas emission limits imposed, many integrated assessments foresee the deployment of CCS systems on a large scale within a few decades from the start of any significant climate change mitigation regime. Energy and economic models indicate that CCS systems

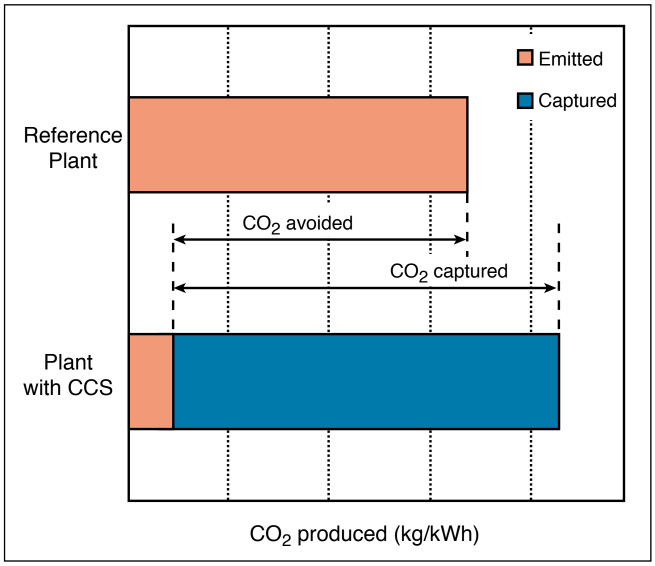

Figure TS.11. CO$_2$ capture and storage from power plants. The increased CO$_2$ production resulting from loss in overall efficiency of power plants due to the additional energy required for capture, transport and storage, and any leakage from transport result in a larger amount of "CO$_2$ produced per unit of product" (lower bar) relative to the reference plant (upper bar) without capture.

are unlikely to contribute significantly to the mitigation of climate change unless deployed in the power sector. For this to happen, the price of carbon dioxide reductions would have to exceed 25–30 US\$/tCO$_2$, or an equivalent limit on CO$_2$ emissions would have to be mandated. The literature and current industrial experience indicate that, in the absence of measures for limiting CO$_2$ emissions, there are only small, niche opportunities for CCS technologies to deploy. These early opportunities involve CO$_2$ captured from a high-purity, low-cost source, the transport of CO$_2$ over distances of less than 50 km, coupled with CO$_2$ storage in a value-added application such as EOR. The potential of such niche options is about 360 MtCO$_2$ per year (see Section 2).

Models also indicate that CCS systems will be competitive with other large-scale mitigation options such as nuclear power and renewable energy technologies. These studies show that including CCS in a mitigation portfolio could reduce the cost of stabilizing CO$_2$ concentrations by 30% or more. One aspect of the cost competitiveness of CCS technologies is that they are compatible with most current energy infrastructures.

In most scenarios, emissions abatement becomes progressively more constraining over time. Most analyses indicate that notwithstanding significant penetration of CCS systems by 2050, the majority of CCS deployment will occur in the second half of this century. The earliest CCS deployments are typically foreseen in the industrialized nations, with deployment eventually spreading worldwide. While results for different scenarios and models differ (often

Table TS.11. Mitigation cost ranges for different combinations of reference and CCS plants based on current technology for new power plants. Currently, in many regions, common practice would be either a PC plant or an NGCC plant[14]. EOR benefits are based on oil prices of 15 - 20 US\$ per barrel. Gas prices are assumed to be 2.8 -4.4 US\$/GJ^{-1}, coal prices 1-1.5 US\$/GJ^{-1} (based on Table 8.3a).

CCS plant type	**NGCC reference plant** **US\$/tCO$_2$ avoided (US\$/tC avoided)**	**PC reference plant** **US\$/tCO$_2$ avoided (US\$/tC avoided)**
Power plant with capture and geological storage		
NGCC	40 - 90 (140 - 330)	20 - 60 (80 - 220)
PC	70 - 270 (260 - 980)	30 - 70 (110 - 260)
IGCC	40 - 220 (150 - 790)	20 - 70 (80 - 260)
Power plant with capture and EOR		
NGCC	20 - 70 (70 - 250)	0 - 30 (0 - 120)
PC	50 - 240 (180 - 890)	10 - 40 (30 - 160)
IGCC	20 - 190 (80 - 710)	0 - 40 (0 - 160)

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[14] IGCC is not included as a reference power plant that would be built today since this technology is not yet widely deployed in the electricity sector and is usually slightly more costly than a PC plant.

significantly) in the specific mix and quantities of different measures needed to achieve a particular emissions constraint (see Figure TS.12), the consensus of the literature shows that CCS could be an important component of the broad portfolio of energy technologies and emission reduction approaches.

The actual use of CCS is likely to be lower than the estimates of economic potential indicated by these energy and economic models. As noted earlier, the results are typically based on an optimized least-cost analysis that does not adequately account for real-world barriers to technology development and deployment, such as environmental impact, lack of a clear legal or regulatory framework, the perceived investment risks of different technologies, and uncertainty as to how quickly the cost of CCS will be reduced through R&D and learning-by-doing. Models typically employ simplified assumptions regarding the costs of CCS for different applications and the rates at which future costs will be reduced.

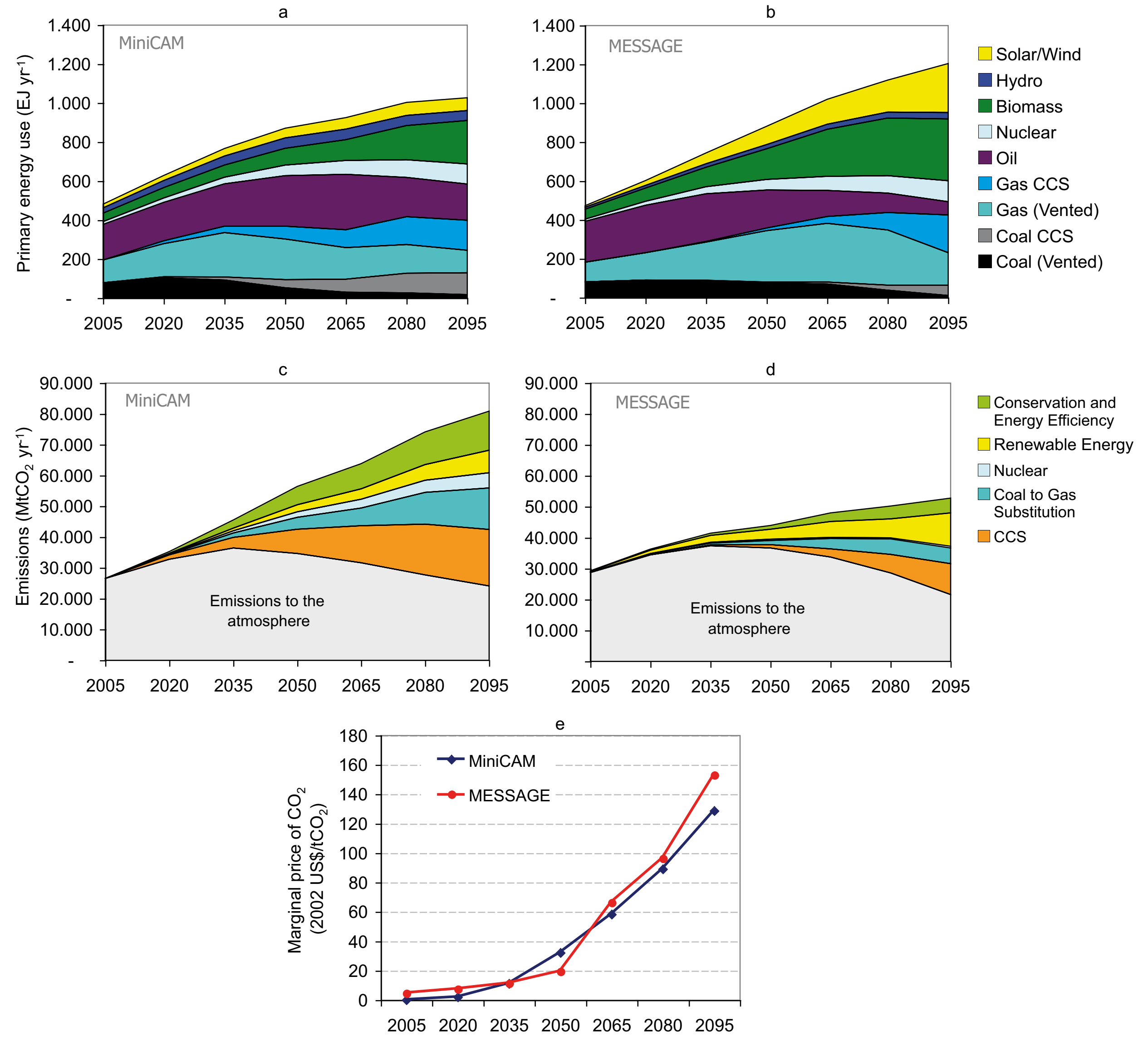

Figure TS.12. These figures are an illustrative example of the global potential contribution of CCS as part of a mitigation portfolio. They are based on two alternative integrated assessment models (MESSAGE and MiniCAM) adopting the same assumptions for the main emissions drivers. The results would vary considerably on regional scales. This example is based on a single scenario and therefore does not convey the full range of uncertainties. Panels a) and b) show global primary energy use, including the deployment of CCS. Panels c) and d) show the global CO_2 emissions in grey and corresponding contributions of main emissions reduction measures in colour. Panel e) shows the calculated marginal price of CO_2 reductions.

For CO_2 stabilization scenarios between 450 and 750 ppmv, published estimates of the cumulative amount of CO_2 potentially stored globally over the course of this century (in geological formations and/or the oceans) span a wide range, from very small contributions to thousands of gigatonnes of CO_2. To a large extent, this wide range is due to the uncertainty of long-term socio-economic, demographic and, in particular, technological changes, which are the main drivers of future CO_2 emissions. However, it is important to note that the majority of results for stabilization scenarios of 450–750 ppmv CO_2 tend to cluster in a range of 220–2,200 $GtCO_2$ (60–600 GtC) for the cumulative deployment of CCS. For CCS to achieve this economic potential, several hundreds or thousands of CCS systems would be required worldwide over the next century, each capturing some 1–5 $MtCO_2$ per year. As indicated in Section 5, it is likely that the technical potential for geological storage alone is sufficient to cover the high end of the economic potential range for CCS.

Perspectives on CO_2 leakage from storage

The policy implications of slow leakage from storage depend on assumptions in the analysis. Studies conducted to address the question of how to deal with impermanent storage are based on different approaches: the value of delaying emissions, cost minimization of a specified mitigation scenario, or allowable future emissions in the context of an assumed stabilization of atmospheric greenhouse gas concentrations. Some of these studies allow future releases to be compensated by additional reductions in emissions; the results depend on assumptions regarding the future cost of reductions, discount rates, the amount of CO_2 stored, and the assumed level of stabilization for atmospheric concentrations. In other studies, compensation is not seen as an option because of political and institutional uncertainties and the analysis focuses on limitations set by the assumed stabilization level and the amount stored.

While specific results of the range of studies vary with the methods and assumptions made, the outcomes suggest that a fraction retained on the order of 90–99% for 100 years or 60–95% for 500 years could still make such impermanent storage valuable for the mitigation of climate change. All studies imply that, if CCS is to be acceptable as a mitigation measure, there must be an upper limit to the amount of leakage that can take place.

9. Emission inventories and accounting

An important aspect of CO_2 capture and storage is the development and application of methods to estimate and report the quantities in which emissions of CO_2 (and associated emissions of methane or nitrous oxides) are reduced, avoided, or removed from the atmosphere. The two elements involved here are (1) the actual estimation and reporting of emissions for national greenhouse gas inventories, and (2) accounting for CCS under international agreements to limit net emissions.[15]

Current framework

Under the UNFCCC, national greenhouse gas emission inventories have traditionally reported emissions for a specific year, and have been prepared on an annual basis or another periodic basis. The IPCC Guidelines (IPCC 1996) and Good Practice Guidance Reports (IPCC 2000; 2003) describe detailed approaches for preparing national inventories that are complete, transparent, documented, assessed for uncertainties, consistent over time, and comparable across countries. The IPCC documents now in use do not specifically include CO_2 capture and storage options. However, the IPCC Guidelines are currently undergoing revisions that should provide some guidance when the revisions are published in 2006. The framework that already has been accepted could be applied to CCS systems, although some issues might need revision or expansion.

Issues relevant to accounting and reporting

In the absence of prevailing international agreements, it is not clear whether the various forms of CO_2 capture and storage will be treated as reductions in emissions or as removals from the atmosphere. In either case, CCS results in new pools of CO_2 that may be subject to physical leakage at some time in the future. Currently, there are no methods available within the UNFCCC framework for monitoring, measuring or accounting for physical leakage from storage sites. However, leakage from well-managed geological storage sites is likely to be small in magnitude and distant in time.

Consideration may be given to the creation of a specific category for CCS in the emissions reporting framework but this is not strictly necessary since the quantities of CO_2 captured and stored could be reflected in the sector in which the CO_2 was produced. CO_2 storage in a given location could include CO_2 from many different source categories, and even from sources in many different countries. Fugitive

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[15] In this context, ''estimation'' is the process of calculating greenhouse gas emissions and ''reporting'' is the process of providing the estimates to the UNFCCC. ''Accounting'' refers to the rules for comparing emissions and removals as reported with commitments (IPCC 2003).

emissions from the capture, transport and injection of CO_2 to storage can largely be estimated within the existing reporting methods, and emissions associated with the added energy required to operate the CCS systems can be measured and reported within the existing inventory frameworks. Specific consideration may also be required for CCS applied to biomass systems as that application would result in reporting negative emissions, for which there is currently no provision in the reporting framework.

Issues relevant to international agreements

Quantified commitments to limit greenhouse gas emissions and the use of emissions trading, Joint Implementation (JI) or the Clean Development Mechanism (CDM) require clear rules and methods to account for emissions and removals. Because CCS has the potential to move CO_2 across traditional accounting boundaries (e.g. CO_2 might be captured in one country and stored in another, or captured in one year and partly released from storage in a later year), the rules and methods for accounting may be different than those used in traditional emissions inventories.

To date, most of the scientific, technical and political discussions on accounting for stored CO_2 have focused on sequestration in the terrestrial biosphere. The history of these negotiations may provide some guidance for the development of accounting methods for CCS. Recognizing the potential impermanence of CO_2 stored in the terrestrial biosphere, the UNFCCC accepted the idea that net emissions can be reduced through biological sinks, but has imposed complex rules for such accounting. CCS is markedly different in many ways from CO_2 sequestration in the terrestrial biosphere (see Table TS.12), and the different forms of CCS are markedly different from one another. However, the main goal of accounting is to ensure that CCS activities produce real and quantifiable reductions in net emissions. One tonne of CO_2 permanently stored has the same benefit in terms of atmospheric CO_2 concentrations as one tonne of CO_2 not emitted, but one tonne of CO_2 temporarily stored has less benefit. It is generally accepted that this difference should be reflected in any system of accounting for reductions in net greenhouse gas emissions.

The IPCC Guidelines (IPCC 1996) and Good Practice Guidance Reports (IPCC 2000; 2003) also contain guidelines for monitoring greenhouse gas emissions. It is not known whether the revised guidelines of the IPCC for CCS can be satisfied by using monitoring techniques, particularly for geological and ocean storage. Several techniques are available for the monitoring and verification of CO_2 emissions from geological storage, but they vary in applicability, detection limits and uncertainties. Currently, monitoring for geological storage can take place quantitatively at injection and qualitatively in the reservoir and by measuring surface fluxes of CO_2. Ocean storage monitoring can take place by

Table TS.12. Differences in the forms of CCS and biological sinks that might influence the way accounting is conducted.

Property	Terrestrial biosphere	Deep ocean	Geological reservoirs
CO_2 sequestered or stored	Stock changes can be monitored over time.	Injected carbon can be measured.	Injected carbon can be measured.
Ownership	Stocks will have a discrete location and can be associated with an identifiable owner.	Stocks will be mobile and may reside in international waters.	Stocks may reside in reservoirs that cross national or property boundaries and differ from surface boundaries.
Management decisions	Storage will be subject to continuing decisions about land-use priorities.	Once injected there are no further human decisions about maintenance once injection has taken place.	Once injection has taken place, human decisions about continued storage involve minimal maintenance, unless storage interferes with resource recovery.
Monitoring	Changes in stocks can be monitored.	Changes in stocks will be modelled.	Release of CO_2 can be detected by physical monitoring.
Expected retention time	Decades, depending on management decisions.	Centuries, depending on depth and location of injection.	Essentially permanent, barring physical disruption of the reservoir.
Physical leakage	Losses might occur due to disturbance, climate change, or land-use decisions.	Losses will assuredly occur as an eventual consequence of marine circulation and equilibration with the atmosphere.	Losses are unlikely except in the case of disruption of the reservoir or the existence of initially undetected leakage pathways.
Liability	A discrete land-owner can be identified with the stock of sequestered carbon.	Multiple parties may contribute to the same stock of stored CO_2 and the CO_2 may reside in international waters.	Multiple parties may contribute to the same stock of stored CO_2 that may lie under multiple countries.

detecting the CO_2 plume, but not by measuring ocean surface release to the atmosphere. Experiences from monitoring existing CCS projects are still too limited to serve as a basis for conclusions about the physical leakage rates and associated uncertainties.

The Kyoto Protocol creates different units of accounting for greenhouse gas emissions, emissions reductions, and emissions sequestered under different compliance mechanisms. 'Assigned amount units' (AAUs) describe emissions commitments and apply to emissions trading, 'certified emission reductions' (CERs) are used under the CDM, and 'emission reduction units' (ERUs) are employed under JI. To date, international negotiations have provided little guidance about methods for calculating and accounting for project-related CO_2 reductions from CCS systems (only CERs or ERUs), and it is therefore uncertain how such reductions will be accommodated under the Kyoto Protocol. Some guidance may be given by the methodologies for biological-sink rules. Moreover, current agreements do not deal with cross-border CCS projects. This is particularly important when dealing with cross-border projects involving CO_2 capture in an 'Annex B' country that is party to the Kyoto Protocol but stored in a country that is not in Annex B or is not bound by the Protocol.

Although methods currently available for national emissions inventories can either accommodate CCS systems or be revised to do so, accounting for stored CO_2 raises questions about the acceptance and transfer of responsibility for stored emissions. Such issues may be addressed through national and international political processes.

10. Gaps in knowledge

This summary of the gaps in knowledge covers aspects of CCS where increasing knowledge, experience and reducing uncertainty would be important to facilitate decision-making about the large-scale deployment of CCS.

Technologies for capture and storage

Technologies for the capture of CO_2 are relatively well understood today based on industrial experience in a variety of applications. Similarly, there are no major technical or knowledge barriers to the adoption of pipeline transport, or to the adoption of geological storage of captured CO_2. However, the integration of capture, transport and storage in full-scale projects is needed to gain the knowledge and experience required for a more widespread deployment of CCS technologies. R&D is also needed to improve knowledge of emerging concepts and enabling technologies for CO_2 capture that have the potential to significantly reduce the costs of capture for new and existing facilities. More specifically, there are knowledge gaps relating to large coal-based and natural gas-based power plants with CO_2 capture on the order of several hundred megawatts (or several $MtCO_2$). Demonstration of CO_2 capture on this scale is needed to establish the reliability and environmental performance of different types of power systems with capture, to reduce the costs of CCS, and to improve confidence in the cost estimates. In addition, large-scale implementation is needed to obtain better estimates of the costs and performance of CCS in industrial processes, such as the cement and steel industries, that are significant sources of CO_2 but have little or no experience with CO_2 capture.

With regard to mineral carbonation technology, a major question is how to exploit the reaction heat in practical designs that can reduce costs and net energy requirements. Experimental facilities at pilot scales are needed to address these gaps.

With regard to industrial uses of captured CO_2, further study of the net energy and CO_2 balance of industrial processes that use the captured CO_2 could help to establish a more complete picture of the potential of this option.

Geographical relationship between the sources and storage opportunities of CO_2

An improved picture of the proximity of major CO_2 sources to suitable storage sites (of all types), and the establishment of cost curves for the capture, transport and storage of CO_2, would facilitate decision-making about large-scale deployment of CCS. In this context, detailed regional assessments are required to evaluate how well large CO_2 emission sources (both current and future) match suitable storage options that can store the volumes required.

Geological storage capacity and effectiveness

There is a need for improved storage capacity estimates at the global, regional and local levels, and for a better understanding of long-term storage, migration and leakage processes. Addressing the latter issue will require an enhanced ability to monitor and verify the behaviour of geologically stored CO_2. The implementation of more pilot and demonstration storage projects in a range of geological, geographical and economic settings would be important to improve our understanding of these issues.

Impacts of ocean storage

Major knowledge gaps that should be filled before the risks and potential for ocean storage can be assessed concern the ecological impact of CO_2 in the deep ocean. Studies are needed of the response of biological systems in the deep sea to added CO_2, including studies that are longer in duration and larger in scale than those that have been performed until now. Coupled with this is a need to develop techniques and sensors to detect and monitor CO_2 plumes and their biological and geochemical consequences.

Legal and regulatory issues

Current knowledge about the legal and regulatory requirements for implementing CCS on a larger scale is still inadequate. There is no appropriate framework to facilitate the implementation of geological storage and take into account the associated long-term liabilities. Clarification is needed regarding potential legal constraints on storage in the marine environment (ocean or sub-seabed geological storage). Other key knowledge gaps are related to the methodologies for emissions inventories and accounting.

Global contribution of CCS to mitigating climate change

There are several other issues that would help future decision-making about CCS by further improving our understanding of the potential contribution of CCS to the long-term global mitigation and stabilization of greenhouse gas concentrations. These include the potential for transfer and diffusion of CCS technologies, including opportunities for developing countries to exploit CCS, its application to biomass sources of CO_2, and the potential interaction between investment in CCS and other mitigation options. Further investigation is warranted into the question of how long CO_2 would need to be stored. This issue is related to stabilization pathways and intergenerational aspects.

1

Introduction

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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. 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:

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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 draft decision called on IPCC to prepare a 'technical paper on geological carbon storage technologies'.

- 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

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 anthropogenic CO_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).

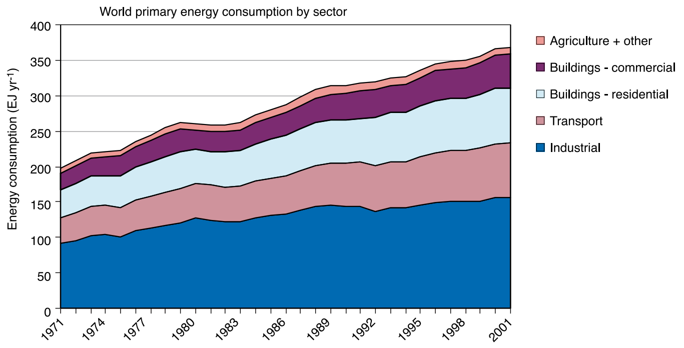

Figure 1.1 World primary energy use by sector from 1971 to 2001 (IEA, 2003).

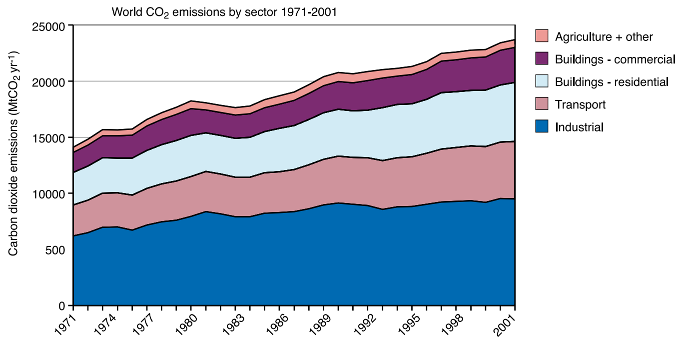

Figure 1.2 World CO_2 emissions from fossil fuel use by sector, 1971 to 2001 (IEA, 2003).

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).

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[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).

Table 1.1 Sources of CO_2 emissions from fossil fuel combustion (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.

1.2.2 Sectoral CO_2 emissions

The CO_2 emissions from various sources worldwide 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.

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 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

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[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).

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 3,480 to 8,050 $GtCO_2$ (950 to 2,200 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):

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

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 6,950 and 9,500 $MtCO_2$ per year (1,900 to 2,600 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 the 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 30 US\$/tCO_2 (100 US\$/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 0.8 to 1.1 US\$/tCO_2 (3-4 US\$/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]. 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

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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.

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).

The potential role of CO_2 capture and storage as a mitigation option has to be examined using 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 1.3b 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

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[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 CO2 is injected underground (Stevens and Gale, 2000).

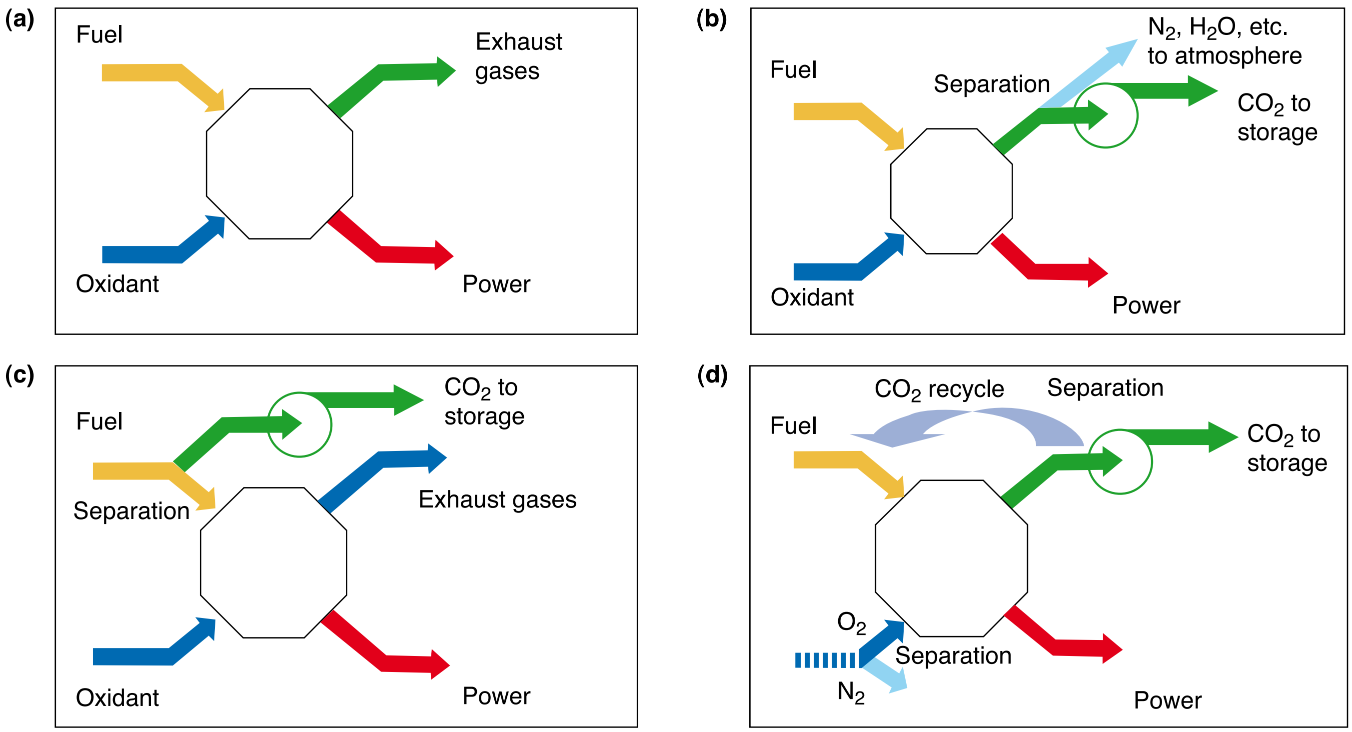

Figure 1.3 a) Schematic diagram of fossil-fuel-based power generation; b) Schematic diagram of post-combustion capture; c) Schematic diagram of pre-combustion capture; d) Schematic diagram of oxyfuel combustion

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 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

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

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.

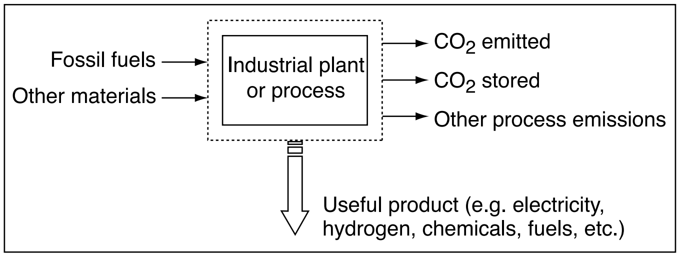

Figure 1.4 System boundary for a plant or process emitting CO_2 (such as a power plant, a hydrogen production plant or other industrial process). The resource and environmental impacts of a CCS system are measured by the changes in total system input and output quantities needed to produce a unit of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

1.5.1 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 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 a 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.

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 a 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.

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\$/tCO_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

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

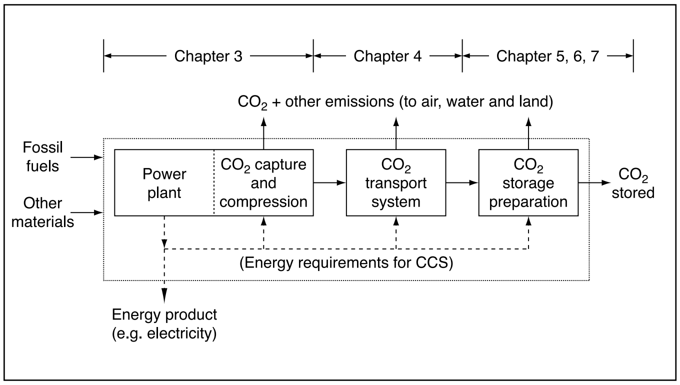

Figure 1.5 System components inside the boundary of Figure 1.4 for the case of a power plant with CO_2 capture and storage. Solid arrows denote mass flows while dashed lines denote energy flows. The magnitude of each flow depends upon the type and design of each sub-system, so only some of the flows 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.

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\$/tCO_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 megawatt 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 Annex I).

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 Annex I 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.

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

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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.

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 in Annex I 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.

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

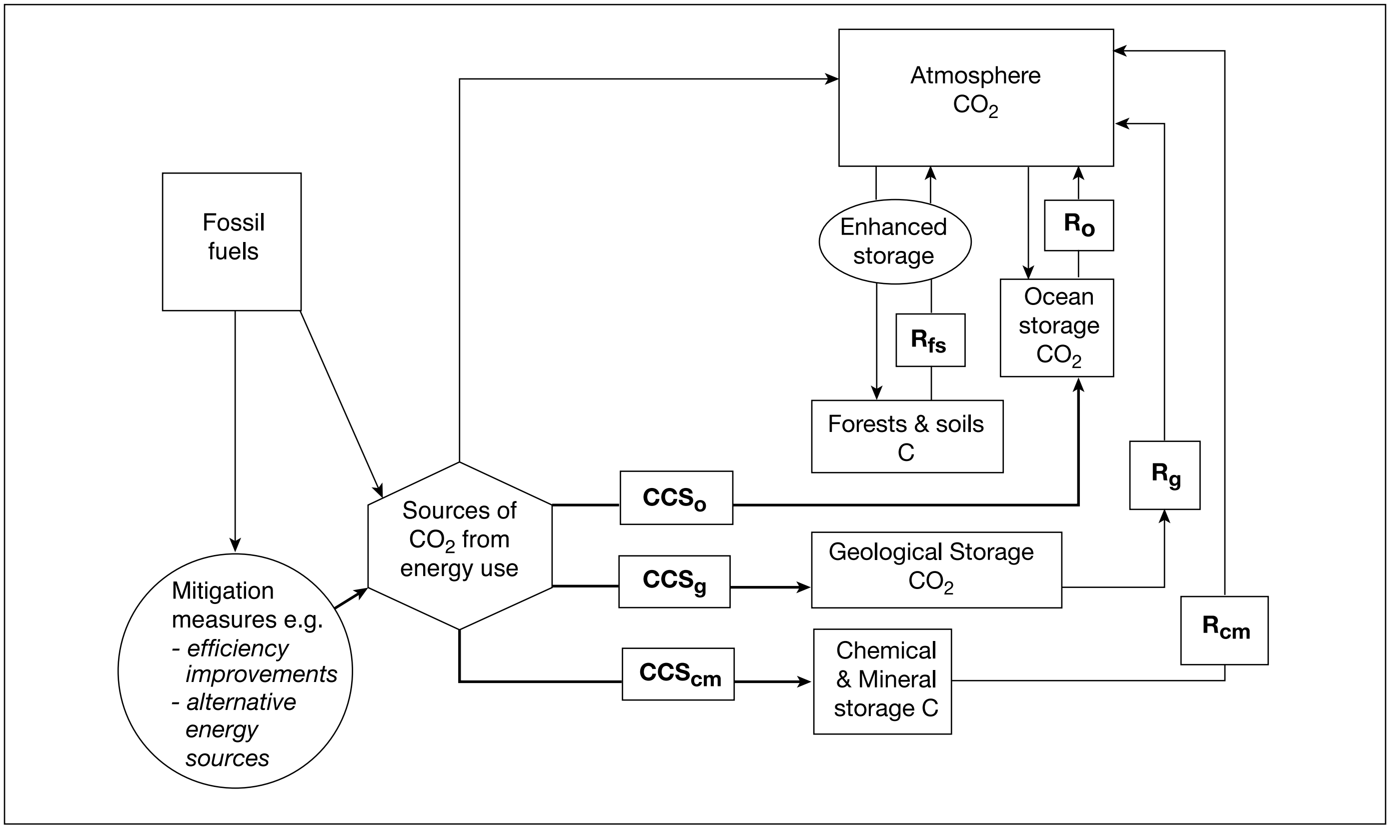

Figure 1.6 Schematic diagram of stocks and flows of CO_2 with net flows of captured CO_2 to each reservoir indicated by the label CCS (these flows exclude residual emissions associated with the process of capture and storage). The release flows from each of the storage reservoirs are indicated by the 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 storing CCS in geological formations, in the oceans or in chemicals or minerals.

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 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

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

[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%.

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 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.

In 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**.

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 is effective action to mitigate climate change, the peak would occur sooner

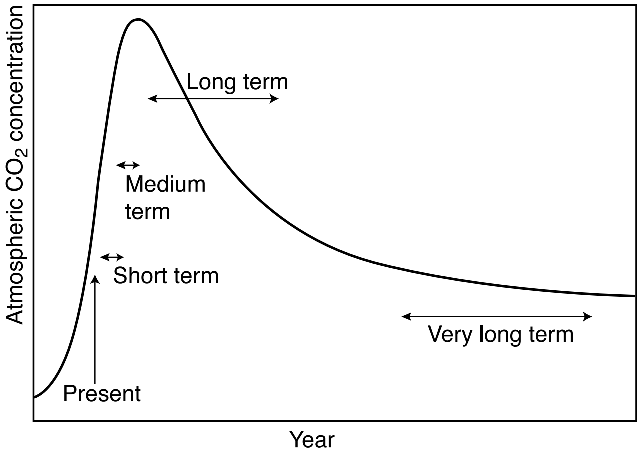

Figure 1.7 The response of atmospheric CO_2 concentrations due to emissions to the atmosphere. Typical values for 'short term', 'medium term', 'long term' and' very long term' are years, decades, centuries, millennia, respectively. In this example, cumulative emissions are limited to a maximum value 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.

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[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.

[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.

(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, although 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).

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

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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.

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, states 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.

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

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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.

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.

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

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[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 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)).

elements will have to be considered (IPCC, 2001a). These are discussed in the IPCC Special Report on Technology Transfer (IPCC, 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 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

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[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).

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

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. Three annexes provide information about the properties of CO_2 and carbon-based fuels, a glossary of terms and the units used in this report. Gaps and areas for further work are discussed in the chapters and in the Technical Summary to this report.

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Sources of CO_2

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Contents

EXECUTIVE SUMMARY

Assessing CO_2 capture and storage calls for a comprehensive delineation of CO_2 sources. The attractiveness of a particular CO_2 source for capture depends on its volume, concentration and partial pressure, integrated system aspects, and its proximity to a suitable reservoir. Emissions of CO_2 arise from a number of sources, mainly fossil fuel combustion in the power generation, industrial, residential and transport sectors. In the power generation and industrial sectors, many sources have large emission volumes that make them amenable to the addition of CO_2 capture technology. Large numbers of small point sources and, in the case of transport, mobile sources characterize the other sectors, making them less amenable for capture at present. Technological changes in the production and nature of transport fuels, however, may eventually allow the capture of CO_2 from energy use in this sector.

Over 7,500 large CO_2 emission sources (above 0.1 $MtCO_2$ yr^{-1}) have been identified. These sources are distributed geographically around the world but four clusters of emissions can be observed: in North America (the Midwest and the eastern freeboard of the USA), North West Europe, South East Asia (eastern coast) and Southern Asia (the Indian sub-continent). Projections for the future (up to 2050) indicate that the number of emission sources from the power and industry sectors is likely to increase, predominantly in Southern and South East Asia, while the number of emission sources suitable for capture and storage in regions like Europe may decrease slightly.

Comparing the geographical distribution of the emission sources with geological storage opportunities, it can be seen that there is a good match between sources and opportunities. A substantial proportion of the emission sources are either on top of, or within 300 km from, a site with potential for geological storage. Detailed studies are, however, needed to confirm the suitability of such sites for CO_2 storage. In the case of ocean storage, related research suggests that only a small proportion of large emission sources will be close to potential ocean storage sites.

The majority of the emissions sources have concentrations of CO_2 that are typically lower than 15%. However, a small proportion (less than 2%) have concentrations that exceed 95%, making them more suitable for CO_2 capture. The high-content sources open up the possibility of lower capture costs compared to low-content sources because only dehydration and compression are required. The future proportion of high- and low-content CO_2 sources will largely depend on the rate of introduction of hydrogen, biofuels, and the gasification or liquefaction of fossil fuels, as well as future developments in plant sizes.

Technological changes, such as the centralized production of liquid or gaseous energy carriers (e.g., methanol, ethanol or hydrogen) from fossil sources or the centralized production of those energy carriers or electricity from biomass, may allow for CO_2 capture and storage. Under these conditions, power generation and industrial emission sources would largely remain unaffected but CO_2 emissions from transport and distributed energy-supply systems would be replaced by additional point sources that would be amenable to capture. The CO_2 could then be stored either in geological formations or in the oceans. Given the scarcity of data, it is not possible to project the likely numbers of such additional point sources, or their geographical distribution, with confidence (estimates range from 0 to 1,400 $GtCO_2$ (0–380 GtC) for 2050).

According to six illustrative SRES scenarios, global CO_2 emissions could range from 29.3 to 44.2 $GtCO_2$ (8–12 GtC) in 2020 and from 22.5 to 83.7 $GtCO_2$ (6–23 GtC) in 2050. The technical potential of CO_2 capture associated with these emission ranges has been estimated recently at 2.6–4.9 $GtCO_2$ for 2020 (0.7–1.3 GtC) and 4.9–37.5 $GtCO_2$ for 2050 (1.3–10 GtC). These emission and capture ranges reflect the inherent uncertainties of scenario and modelling analyses. However, there is one trend common to all of the six illustrative SRES scenarios: the general increase of future CO_2 emissions in the developing countries relative to the industrialized countries.

2.1 Sources of CO_2

This chapter aims to consider the emission sources of CO_2 and their suitability for capture and subsequent storage, both now and in the future. In addition, it will look at alternative energy carriers for fossil fuels and at how the future development of this technology might affect the global emission sources of CO_2 and the prospects for capturing these emissions.

Chapter 1 showed that the power and industry sectors combined dominate current global CO_2 emissions, accounting for about 60% of total CO_2 emissions (see Section 1.2.2). Future projections indicate that the share of these sectoral emissions will decline to around 50% of global CO_2 emissions by 2050 (IEA, 2002). The CO_2 emissions in these sectors are generated by boilers and furnaces burning fossil fuels and are typically emitted from large exhaust stacks. These stacks can be described as large stationary sources, to distinguish them from mobile sources such as those in the transport sector and from smaller stationary sources such as small heating boilers used in the residential sector. The large stationary sources represent potential opportunities for the addition of CO_2 capture plants. The volumes produced from these sources are usually large and the plants can be equipped with a capture plant to produce a source of high-purity CO_2 for subsequent storage. Of course, not all power generation and industrial sites produce their emissions from a single point source. At large industrial complexes like refineries there will be multiple exhaust stacks, which present an additional technical challenge in terms of integrating an exhaust-gas gathering system in an already congested complex, undoubtedly adding to capture costs (Simmonds *et al.*, 2003).

Coal is currently the dominant fuel in the power sector, accounting for 38% of electricity generated in 2000, with hydro power accounting for 17.5%, natural gas for 17.3%, nuclear for 16.8%, oil for 9%, and non-hydro renewables for 1.6%. Coal is projected to remain the dominant fuel for power generation in 2020 (about 36%), whilst natural-gas generation will become the second largest source, surpassing hydro. The use of biomass as a fuel in the power sector is currently limited. Fuel selection in the industrial sector is largely sector-specific. For example, the use of blast furnaces dominates primary steel production in the iron and steel sector, which primarily uses coal and coke (IEA GHG, 2000b; IPCC, 2001). In the refining and chemical sectors, oil and gas are the primary fuels. For industries like cement manufacture, all fossil fuels are used, with coal dominating in areas like the USA, China and India (IEA GHG, 1999), and oil and gas in countries like Mexico (Sheinbaum and Ozawa, 1998). However, the current trend in European cement manufacture is to use non-fossil fuels: these consist principally of wastes like tyres, sewage sludge and chemical-waste mixtures (IEA GHG, 1999). In global terms, biomass is not usually a significant fuel source in the large manufacturing industries. However, in certain regions of the world, like Scandinavia and Brazil, it is acknowledged that biomass use can be significant (Möllersten *et al.*, 2003).

To reduce the CO_2 emissions from the power and industry sectors through the use of CO_2 capture and storage, it is important to understand where these emissions arise and what their geographical relationship is with respect to potential storage opportunities (Gale, 2002). If there is a good geographical relationship between the large stationary emission sources and potential geological storage sites then it is possible that a significant proportion of the emissions from these sources can be reduced using CO_2 capture and storage. If, however, they are not well matched geographically, then there will be implications for the length and size of the transmission infrastructure that is required, and this could impact significantly on the cost of CO_2 capture and storage, and on the potential to achieve deep reductions in global CO_2 emissions. It may be the case that there are regions of the world that have greater potential for the application of CO_2 capture and storage than others given their source/storage opportunity relationship. Understanding the regional differences will be an important factor in assessing how much of an impact CO_2 capture and storage can have on global emissions reduction and which of the portfolio of mitigation options is most important in a regional context.

Other sectors of the economy, such as the residential and transport sectors, contribute around 30% of global CO_2 emissions and also produce a large number of point source emissions. However, the emission volumes from the individual sources in these sectors tend to be small in comparison to those from the power and industry sectors and are much more widely distributed, or even mobile rather than stationary. It is currently not considered to be technically possible to capture emissions from these other small stationary sources, because there are still substantial technical and economic issues that need to be resolved (IPCC, 2001). However, in the future, the use of low-carbon energy carriers, such as electricity or hydrogen produced from fossil fuels, may allow CO_2 emissions to be captured from the residential and transport sectors as well. Such fuels would most probably be produced in large centralized plants and would be accompanied by capture and storage of the CO_2 co-product. The distributed fuels could then be used for distributed generation in either heaters or fuels cells and in vehicles in the transport sector. In this scenario, power generation and industrial sources would be unaffected but additional point sources would be generated that would also require storage. In the medium to long term therefore, the development and commercial deployment of such technology, combined with an accelerated shift to low- or zero-carbon fuels in the transport sector, could lead to a significant change in the geographical pattern of CO_2 emissions compared to that currently observed.

2.2 Characterization of CO_2 emission sources

This section presents information on the characteristics of the CO_2 emission sources. It is considered necessary to review the different CO_2 contents and volumes of CO_2 from these sources as these factors can influence the technical suitability of these emissions for storage, and the costs of capture and storage.

2.2.1 Present

2.2.1.1 Source types

The emission sources considered in this chapter include all large stationary sources (>0.1 $MtCO_2$ yr^{-1}) involving fossil fuel and biomass use. These sources are present in three main areas: fuel combustion activities, industrial processes and natural-gas processing. The largest CO_2 emissions by far result from the oxidation of carbon when fossil fuels are burned. These emissions are associated with fossil fuel combustion in power plants, oil refineries and large industrial facilities.

For the purposes of this report, large stationary sources are considered to be those emitting over 0.1 $MtCO_2$ yr^{-1}. This threshold was selected because the sources emitting less than 0.1 $MtCO_2$ yr^{-1} together account for less than 1% of the emissions from all the stationary sources under consideration (see Table 2.1). However, this threshold does not exclude emissions capture at smaller CO_2 sources, even though this is more costly and technically challenging.

Carbon dioxide not related to combustion is emitted from a variety of industrial production processes which transform materials chemically, physically or biologically. Such processes include:

- the use of fuels as feedstocks in petrochemical processes (Chauvel and Lefebvre, 1989; Christensen and Primdahl, 1994);
- the use of carbon as a reducing agent in the commercial production of metals from ores (IEA GHG, 2000; IPCC, 2001);
- the thermal decomposition (calcination) of limestone and dolomite in cement or lime production (IEA GHG, 1999, IPCC 2001);
- the fermentation of biomass (e.g., to convert sugar to alcohol).

In some instances these industrial-process emissions are produced in combination with fuel combustion emissions, a typical example being aluminium production (IEA GHG, 2000).

Table 2.1 Properties of candidate gas streams that can be inputted to a capture process (Sources: Campbell et al., 2000; Gielen and Moriguchi, 2003; Foster Wheeler, 1998; IEA GHG, 1999; IEA GHG, 2002a).

Source	CO_2 concentration % vol (dry)	Pressure of gas stream MPa[a]	CO_2 partial pressure MPa
CO_2 from fuel combustion			
• Power station flue gas:			
Natural gas fired boilers	7 - 10	0.1	0.007 - 0.010
Gas turbines	3 - 4	0.1	0.003 - 0.004
Oil fired boilers	11 - 13	0.1	0.011 - 0.013
Coal fired boilers	12 - 14	0.1	0.012 - 0.014
IGCC[b]: after combustion	12 - 14	0.1	0.012 - 0.014
• Oil refinery and petrochemical plant fired heaters	8	0.1	0.008
CO_2 from chemical transformations + fuel combustion			
• Blast furnace gas:			
Before combustion[c]	20	0.2 - 0.3	0.040 - 0.060
After combustion	27	0.1	0.027
• Cement kiln off-gas	14 - 33	0.1	0.014 - 0.033
CO_2 from chemical transformations before combustion			
• IGCC: synthesis gas after gasification	8 - 20	2 - 7	0.16 - 1.4

[a] 0.1 MPa = 1 bar.
[b] IGCC: Integrated gasification combined cycle.
[c] Blast furnace gas also contains significant amounts of carbon monoxide that could be converted to CO_2 using the so-called shift reaction.

A third type of source occurs in natural-gas processing installations. CO_2 is a common impurity in natural gas, and it must be removed to improve the heating value of the gas or to meet pipeline specifications (Maddox and Morgan, 1998).

2.2.1.2 CO_2 content

The properties of those streams that can be inputted to a CO_2 capture process are discussed in this section. In CO_2 capture, the CO_2 partial pressure of the gas stream to be treated is important as well as the concentration of the stream. For practical purposes, this partial pressure can be defined as the product of the total pressure of the gas stream times the CO_2 mole fraction. It is a key variable in the selection of the separation method (this is discussed further in Chapter 3). As a rule of thumb, it can be said that the lower the CO_2 partial pressure of a gas stream, the more stringent the conditions for the separation process.

Typical CO_2 concentrations and their corresponding partial pressures for large stationary combustion sources are shown in Table 2.1, which also includes the newer Integrated Gasification Combined Cycle technology (IGCC). Typically, the majority of emission sources from the power sector and from industrial processes have low CO_2 partial pressures; hence the focus of the discussion in this section. Where emission sources with high partial pressure are generated, for example in ammonia or hydrogen production, these sources require only dehydration and some compression, and therefore they have lower capture costs.

Table 2.1 also provides a summary of the properties of CO_2 streams originating from cement and metal production in which chemical transformations and combustion are combined. Flue gases found in power plants, furnaces in industries, blast furnaces and cement kilns are typically generated at atmospheric pressure and temperatures ranging between 100°C and 200°C, depending on the heat recovery conditions.

Carbon dioxide levels in flue gases vary depending on the type of fuel used and the excess air level used for optimal combustion conditions. Flue gas volumes also depend on these two variables. Natural-gas-fired power generation plants are typically combined cycle gas turbines which generate flue gases with low CO_2 concentrations, typically 3–4% by volume (IEA GHG, 2002a). Coal for power generation is primarily burnt in pulverized-fuel boilers producing an atmospheric pressure flue gas stream with a CO_2 content of up to 14% by volume (IEA GHG, 2002a). The newer and potentially more efficient IGCC technology has been developed for generating electricity from coal, heavy fuel oil and process carbonaceous residues. In this process the feedstock is first gasified to generate a synthesis gas (often referred to as 'syngas'), which is burnt in a gas turbine after exhaustive gas cleaning (Campbell *et al.*, 2000). Current IGCC plants where the synthesis gas is directly combusted in the turbine, like conventional thermal power plants, produce a flue gas with low CO_2 concentrations (up to 14% by volume). At present, there are only fifteen coal- and oil-fired IGCC plants, ranging in size from 40 to 550 MW. They were started up in the 1980s and 1990s in Europe and the USA (Giuffrida *et al.*, 2003). It should be noted that there are conceptual designs in which the CO_2 can be removed before the synthesis gas is combusted, producing a high-concentration, high-pressure CO_2 exhaust gas stream that could be more suitable for storage (see Chapter 3 for more details). However, no such plants have been built or are under construction.

Fossil fuel consumption in boilers, furnaces and in process operations in the manufacturing industry also typically produces flue gases with low CO_2 levels comparable to those in the power

Table 2.2 Typical properties of gas streams that are already input to a capture process (Sources: Chauvel and Lefebvre, 1989; Maddox and Morgan, 1998; IEA GHG, 2002a).

Source	CO_2 concentration % vol	Pressure of gas stream MPa[a]	CO_2 partial pressure MPa
Chemical reaction(s)			
• Ammonia production[b]	18	2.8	0.5
• Ethylene oxide	8	2.5	0.2
• Hydrogen production[b]	15 - 20	2.2 - 2.7	0.3 - 0.5
• Methanol production[b]	10	2.7	0.27
Other processes			
• Natural gas processing	2 - 65	0.9 - 8	0.05 - 4.4

[a] 0.1 MPa = 1 bar

[b] The concentration corresponds to high operating pressure for the steam methane reformer.

sector. CO_2 concentrations in the flue gas from cement kilns depend on the production process and type of cement produced and are usually higher than in power generation processes (IEA GHG, 1999). Existing cement kilns in developing countries such as China and India are often relatively small. However, the quantity of CO_2 produced by a new large cement kiln can be similar to that of a power station boiler. Integrated steel mills globally account for over 80% of CO_2 emissions from steel production (IEA GHG, 2000b). About 70% of the carbon input to an integrated steel mill is present in the blast furnace gas, which is used as a fuel gas within the steel mill. CO_2 could be captured before or after combustion of this gas. The CO_2 concentration after combustion in air would be about 27% by volume, significantly higher than in the flue gas from power stations. Other process streams within a steel mill may also be suitable candidates for CO_2 capture before or after combustion. For example, the off-gas from an oxygen-steel furnace typically contains 16% CO_2 and 70% carbon monoxide.

The off-gases produced during the fermentation of sugars to ethanol consist of almost pure CO_2 with a few impurities. This gas stream is generated at a rate of 0.76 kg CO_2^{-1} and is typically available at atmospheric pressure (0.1 MPa) (Kheshgi and Prince, 2005).

CO_2 also occurs as an undesirable product that must be removed in some petrochemical processes, particularly those using synthesis gas as an intermediate or as an impurity in natural gas. The properties of the raw gas streams from which CO_2 is customarily removed in some of these industries are shown in Table 2.2. It can be seen from Table 2.1 that the CO_2 partial pressures of flue gases are at least one order of magnitude less than the CO_2 partial pressures of the streams arising from the processes listed in Table 2.2. This implies that CO_2 recovery from fuel combustion streams will be comparatively much more difficult.

2.2.1.3 Scale of emissions

A specific detailed dataset has been developed for CO_2 stationary sources for 2000, giving their geographical distribution by process type and country (IEA GHG, 2002a). The stationary sources of CO_2 in this database comprise power plants, oil refineries, gas-processing plants, cement plants, iron and steel plants and those industrial facilities where fossil fuels are used as feedstock, namely ammonia, ethylene, ethylene oxide and hydrogen. This global inventory contains over 14 thousand emission sources with individual CO_2 emissions ranging from 2.5 $tCO_2\ yr^{-1}$ to 55.2 $MtCO_2\ yr^{-1}$. The information for each single source includes location (city, country and region), annual CO_2 emissions and CO_2 emission concentrations. The coordinates (latitude/longitude) of 74% of the sources are also provided. The total emissions from these 14 thousand sources amount to over 13 $GtCO_2\ yr^{-1}$. Almost 7,900 stationary sources with individual emissions greater than or equal to 0.1 $MtCO_2$ per year have been identified globally. These emissions included over 90% of the total CO_2 emissions from large point sources in 2000. Some 6,000 emission sources with emissions below 0.1 $MtCO_2\ yr^{-1}$ were also identified, but they represent only a small fraction of the total emissions volume and were therefore excluded from further discussion in this chapter. There are also a number of regional and country-specific CO_2 emission estimates for large sources covering China, Japan, India, North West Europe and Australia (Hibino, 2003; Garg *et al.*, 2002; Christensen *et al.*, 2001, Bradshaw *et al.*, 2002) that can be drawn upon. Table 2.3 summarizes the information concerning large stationary sources according to the type of emission generating process. In the case of the petrochemical and gas-processing industries, the CO_2 concentration listed in this table refers to the stream leaving the capture process. The largest amount of CO_2 emitted from large stationary sources originates from fossil fuel combustion for power generation, with an average annual emission of 3.9 $MtCO_2$ per source. Substantial amounts of CO_2 arise in the oil and gas processing industries while cement production is the largest emitter from the industrial sector.

In the USA, 12 ethanol plants with a total productive capacity of 5.3 billion litres yr^{-1} each produce CO_2 at rates in excess of 0.1 $MtCO_2\ yr^{-1}$ (Kheshgi and Prince, 2005); in Brazil, where ethanol production totalled over 14 billion litres per year during 2003-2004, the average distillery productive capacity is 180 million litres yr^{-1}. The corresponding average fermentation CO_2 production rate is 0.14 $MtCO_2\ yr^{-1}$, with the largest distillery producing nearly 10 times the average.

Table 2.3 Profile of worldwide large CO_2 stationary sources emitting more than 0.1 Mt CO_2 per year (Source: IEA GHG, 2002a).

Process	**CO_2 concentration in gas stream % by vol.**	**Number of sources**	**Emissions (MtCO$_2$)**	**% of total CO_2 emissions**	**Cumulative total CO_2 emissions (%)**	**Average emissions/source (MtCO$_2$ per source)**
CO_2 from fossil fuels or minerals						
Power						
Coal	12 to 15	2,025	7,984	59.69	59.69	3.94
Natural gas	3	985	759	5.68	65.37	0.77
Natural gas	7 to 10	743	752	5.62	70.99	1.01
Fuel oil	8	515	654	4.89	75.88	1.27
Fuel oil	3	593	326	2.43	78.31	0.55
Other fuels[a]	NA	79	61	0.45	78.77	0.77
Hydrogen	NA	2	3	0.02	78.79	1.27
Natural-gas sweetening						
	NA[b]	NA	50[c]	0.37	79.16	
Cement production						
Combined	20	1175	932	6.97	86.13	0.79
Refineries						
	3 to 13	638	798	5.97	92.09	1.25
Iron and steel industry						
Integrated steel mills	15	180	630[d]	4.71	96.81	3.50
Other processes[d]	NA	89	16	0.12	96.92	0.17
Petrochemical industry						
Ethylene	12	240	258	1.93	98.85	1.08
Ammonia: process	100	194	113	0.84	99.70	0.58
Ammonia: fuel combustion	8	19	5	0.04	99.73	0.26
Ethylene oxide	100	17	3	0.02	99.75	0.15
Other sources						
Non-specified	NA	90	33	0.25	100.00	0.37
		7,584	**13,375**	**100**		**1.76**
CO_2 from biomass[e]						
Bioenergy	3 to 8	213	73			0.34
Fermentation	100	90	17.6			**0.2**

[a] Other gas, other oil, digester gas, landfill gas.

[b] A relatively small fraction of these sources has a high concentration of CO_2. In Canada, only two plants out of a total of 24 have high CO_2 concentrations.

[c] Based on an estimate that about half of the annual worldwide natural-gas production contains CO_2 at concentrations of about 4% mol and that this CO_2 content is normally reduced from 4% to 2% mol (see Section 3.2.2).

[d] This amount corresponds to the emissions of those sources that have been individually identified in the reference database. The worldwide CO_2 emissions, estimated by a top-down approach, are larger than this amount and exceed 1 Gt (Gielen and Moriguchi, 2003).

[e] For North America and Brazil only. All numbers are for 2003, except for power generation from biomass and waste in North America, which is for 2000.

The top 25% of all large stationary CO_2 emission sources (those emitting more than 1 MtCO$_2$ per year) listed in Table 2.3 account for over 85% of the cumulative emissions from these types of sources. At the other end of the scale, the lowest 41% (in the 0.1 to 0.5 MtCO$_2$ range) contribute less than 10% (Figure 2.1). There are 330 sources with individual emissions above 10 MtCO$_2$ per year. Of their cumulative emissions, 78% come from power plants, 20% from gas processing and the remainder from iron and steel plants (IEA GHG, 2000b). High-concentration/high-partial-pressure sources (e.g., from ammonia/hydrogen production and gas processing operations) contribute a relatively low share (<2%) of the emissions from large stationary sources (van Bergen *et al*., 2004). However, these high-concentration sources could represent early prospects for the implementation of CO_2 capture and storage. The costs for capture are lower than for low-concentration/low-partial-pressure sources. If these sources can then be linked to enhanced production schemes in the vicinity (<50km), like CO_2-enhanced oil recovery, they could be low-cost options for CO_2 capture and storage (van Bergen *et al.*, 2004). Such sources emit 0.36 $GtCO_2\ yr^{-1}$ (0.1 $GtC\ yr^{-1}$), which equates to 3% of emissions from point sources larger than 0.1 $MtCO_2\ yr^{-1}$ (IEA GHG, 2002b). The geographical relationship between these high-concentration sources and prospective storage opportunities is discussed in Section 2.4.3. A small number of source streams with high CO_2 concentrations are already used in CO_2-EOR operations in the USA and Canada (Stevens and Gale, 2000).

2.2.2 Future

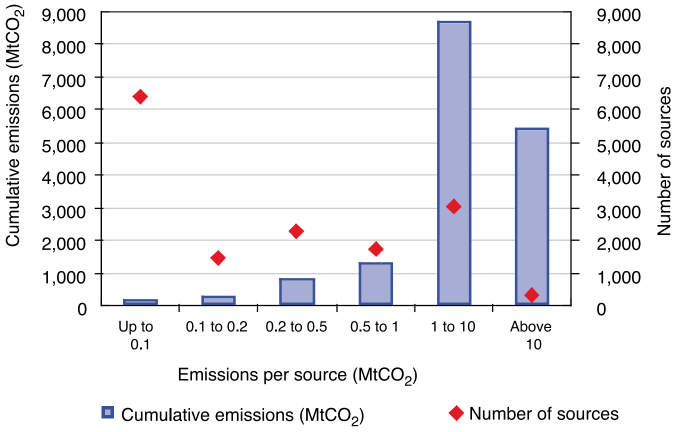

Figure 2.1 Relationship between large stationary source emissions and number of emission sources (Source: IEA GHG, 2002a).

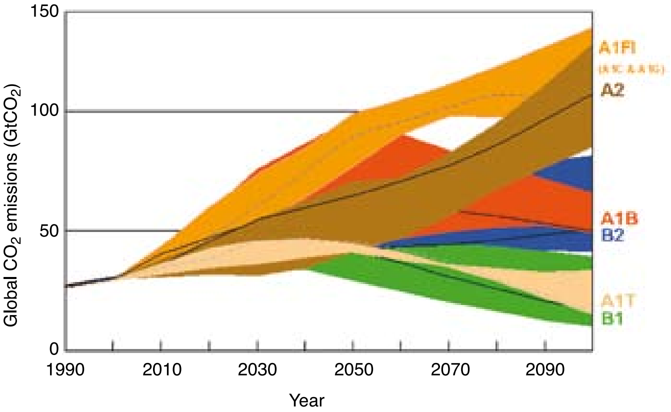

Figure 2.2 Range of annual global CO_2 emission in he SRES scenarios ($GtCO_2$) (Source: IPCC, 2000).

Future anthropogenic CO_2 emissions will be the product of different drivers such as demographic development, socio-economic development, and technological changes (see Chapter 1, Section 1.2.4). Because their future evolution is inherently uncertain and because numerous combinations of different rates of change are quite plausible, analysts resort to scenarios as a way of describing internally consistent, alternative images of how the future might unfold. The IPCC developed a set of greenhouse gas emission scenarios for the period until 2100 (IPCC, 2000). The scenarios show a wide range of possible future worlds and CO_2 emissions (see Figure 2.2), consistent with the full uncertainty range of the underlying literature reported by Morita and Lee (1998). The scenarios are important as they provide a backdrop for determining the baseline for emission reductions that may be achieved with new technologies, including CO_2 capture and storage implemented specially for such purposes.

Technology change is one of the key drivers in long-term scenarios and plays a critical role in the SRES scenarios. Future rates of innovation and diffusion are integral parts of, and vary with, the story lines. Scenario-specific technology change may differ in terms of technology clusters (i.e., the type of technologies used) or rate of diffusion. In the fossil-intensive A1FI scenario, innovation concentrates on the fossil source-to-service chains stretching from exploration and resource extraction to fuel upgrading/cleaning, transport, conversion and end-use. Alternatively, innovation in the environmentally-oriented B1 scenario focuses on renewable and hydrogen technologies.

The way in which technology change was included in the SRES scenarios depended on the particular model used. Some models applied autonomous performance improvements to fuel utilization, while others included specific technologies with detailed performance parameters. Even models with a strong emphasis on technology reflected new technologies or innovation in a rather generic manner. For example, advanced coal technology could be either an integrated coal gasification combined cycle (IGCC) plant, a pressurized fluidized bed combustion facility or any other, as-yet-unidentified, technology. The main characteristics of advanced coal technology are attractive investment costs, high thermal efficiency, potential multi-production integration and low pollution emissions – features that are prerequisites for any coal technology carrying the “advanced” label.

In general, technological diversity remained a feature in all scenarios, despite the fact that different clusters may dominate more in different scenarios. The trend towards cleaner and more convenient technologies, especially at the level of end-use (including transport), is common to all scenarios. In addition, transport fuels shift broadly towards supply schemes suitable for pre-combustion decarbonization. Centralized non-fossil technologies penetrate the power sector to various extents, while decentralized and home-based renewable and hydrogen-production infrastructures expand in all scenarios, but mostly in the environmentally-conscious and technology-intensive scenarios.

Despite the trend towards cleaner fuels, CO_2 emissions are projected to rise at different rates, at least until 2050. Emission patterns then diverge. Scenario-specific rates of technology change (performance improvements) and technology diffusion lead to different technology mixes, fuel uses and unit sizes. As regards fossil fuel use for power generation and industrial energy supply, the number of large stationary emission sources generally increases in the absence of restrictions on CO_2 emissions and a fundamental change in the characteristics of these emission

Table 2.4 Sectoral and regional distribution of energy-related CO$_2$ emissions in 2000 (MtCO$_2$) (Source: IEA, 2003).

		Public electricity and heat production	Unallocated autoproducers	Other energy industries	Manufacturing industries and construction	Transport	Commercial and public services	Residential	Other sectors	CO$_2$ sectoral approach total
1	Economies in transition	1,118.5	391.4	106.6	521.7	317.1	58.0	312.5	127.7	2,953.6
2	OECD West	1,087.3	132.0	222.8	722.1	1,040.9	175.1	494.6	96.2	3,971.0
3	USA	2,265.1	134.9	272.4	657.9	1,719.9	225.5	371.4	42.7	5,689.7
4	OECD Pacific	509.2	87.0	62.2	301.1	344.4	95.3	75.8	35.7	1,510.5
5	South/East Asia	925.5	104.1	137.9	533.3	451.8	50.9	185.6	39.7	2,428.7
6	Centrally Planned Asia	1,332.2	37.7	138.5	978.4	245.4	72.6	221.4	118.7	3,144.8
7	Middle East	280.6	6.6	118.6	193.0	171.6	16.6	90.8	112.5	990.4
8	Africa	276.3	15.9	40.2	137.7	143.5	5.0	44.5	34.8	697.8
9	Latin America	222.3	37.0	134.5	279.3	396.0	17.9	81.0	41.5	1,209.6
	Sector total	**8,016.9**	**946.5**	**1,233.7**	**4,324.7**	**4,830.6**	**716.8**	**1,877.5**	**649.4**	**22,596.1**

sources is unlikely to occur before 2050. In addition, the ratio of low-concentration to high-concentration emission sources remains relatively stable, with low-concentration sources dominating the emission profile.

In some scenarios, low- or zero-carbon fuels such as ethanol, methanol or hydrogen begin to dominate the transport sector and make inroads into the industrial, residential and commercial sectors after 2050. The centralized production of such fuels could lead to a significant change in the number of high-concentration emission sources and a change in the ratio of low- to high-purity emission sources; this is discussed in more detail in Section 2.5.2.

2.3 Geographical distribution of sources

This section discusses the geographical locations of large point sources discussed in the preceding sections. It is necessary to understand how these sources are geographically distributed across the world in order to assess their potential for subsequent storage.

2.3.1 Present

A picture of the geographical distribution of the sources of CO$_2$ emissions and the potential storage reservoirs helps us to understand the global cost of CO$_2$ mitigation, particularly those components associated with CO$_2$ transport. Geographical information about emission sources can be retrieved from a number of data sets. Table 2.4 shows the sectoral and regional distribution of energy-related CO$_2$ emissions in 2000. As mentioned earlier in this report, over 60% of global CO$_2$ emissions come from the power and industry sectors. Geographically, these power and industry emissions are dominated by four regions which account for over 90% of the emissions. These regions are: Asia (30%), North America (24%), the transitional economies (13%), and OECD West[1] (12%). All the other regions account individually for less than 6% of the global emissions from the power and industry sectors.

Figure 2.3 shows the known locations of stationary CO$_2$ sources worldwide, as taken from the database referred to in Section 2.2 (IEA GHG, 2002a). North America is the region with the largest number of stationary sources (37%), followed by Asia (24%) and OECD Europe[2] (14%). Figure 2.3 shows three large clusters of stationary sources located in the central and eastern states of the US, in northwestern and central regions of Europe (Austria, Czech Republic, Germany, Hungary, Netherlands and UK) and in Asia (eastern China and Japan with an additional smaller cluster in the Indian subcontinent).

The distribution of stationary CO$_2$ emissions as a proportion of the total stationary emissions for 2000 indicates that the regions that are the largest emitters of CO$_2$ from stationary sources are: Asia at 41% (5.6 GtCO$_2$ yr^{-1}), North America at 20% (2.69 GtCO$_2$ yr^{-1}) and OECD Europe at 13% (1.75 GtCO$_2$ yr^{-1}). All other regions emitted less than 10% of the total CO$_2$ emission from stationary sources in 2000.

A comparison of the estimates of CO$_2$ emissions from the IEA and IEA GHG databases showed that the two sets produced

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[1] Note: OECD West refers to the following countries: Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom.

[2] OECD Europe includes the OECD West countries listed above, plus the Czech Republic, Hungary, Iceland, Norway, Poland, Slovak Republic, Switzerland and Turkey.

Figure 2.3 Global distribution of large stationary CO_2 sources (based on a compilation of publicly available information on global emission sources, IEA GHG 2002).

similar estimates for the total of global emissions but that results differed significantly for many countries. Regional differences of this kind have also been noted for other CO_2 emission databases (Marland *et al*., 1999).

2.3.2 Future CO_2 emissions and technical capture potentials

The total CO_2 emissions from fossil fuel combustion in the SRES scenarios provide the upper limit for potential CO_2 capture for this assessment. In fact, the theoretical maximum is even higher because of the possibility of CO_2 capture from biomass. These emissions are also included in the tables of CO_2 emissions and they are therefore potentially available for capture. Obviously, the capture potential that is practical in technical terms is much smaller than the theoretical maximum, and the economic potential[3] is even smaller. Needless to say, it is the economic potential that matters most. This section presents estimates of the technical potential and Chapter 8 will address the economic potential.

Table 2.5 shows the CO_2 emissions by economic sector and major world regions for 2020 and 2050, and for six scenarios[4]. It should be noted that the total CO_2 emissions in Table 2.5 are higher than reported in SRES because emissions from biomass are explicitly included here (as these are potentially available for capture), while they where considered "climate-neutral" in the SRES presentations and therefore not counted as emission releases to the atmosphere. Geographically, the distribution of emission sources is set to change substantially. Between 2000 and 2050, the bulk of emission sources will shift from the OECD countries to the developing regions, especially China, South Asia and Latin America. As to emissions by sector, power generation, transport, and industry will remain the three main sources of CO_2 emissions over the next 50 years. Globally, the projected energy sector emissions will fluctuate around the 40% mark in 2050 (this matches the current figure), emissions from the industry sector will decline and transport sector emissions (i.e., mobile sources) increase. Power generation, which typically represent the bulk of large point sources, will account for about 50% of total emissions by 2050[5].

These emissions form the theoretical maximum potential for CO_2 capture from fossil fuel use. Toth and Rogner (2006) derived a set of capture factors on the basis of the technical or technological feasibility of adding CO_2 capture before, during or after combustion of fossil fuels. Capture factors are defined as the estimated maximum share of emissions for which capture is technically plausible. A detailed assessment of the power plants

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[3] Economic potential is the amount of reductions in greenhouse gas emissions from a specific option that could be achieved cost-effectively given prevailing circumstances (i.e. a price for CO_2 reductions and the costs of other options).

[4] For the four marker scenarios and the technology-intensive A1T and the fossil-intensive A1FI illustrative scenarios, it is important to note that comparisons between the results of different models are not straightforward. First, the modelling methodologies imply different representations of energy technologies and their future evolutions. Secondly, the sectoral disaggregation and the energy/fuel details vary across the models. Thirdly, there are differences in how countries of the world are grouped together into regions. Tables 2.5 and 2.6 are based on the work by Toth and Rogner (2005) that attempts to create the best possible approximation for the purposes of comparing the regional and sectoral model and scenario results.

[5] As regards the share of emissions across sectors in 2020 (Table 2.5), there is an inherent divergence between scenarios with longer and shorter time horizons. Given the quasi perfect foresight of the underlying models, the SRES scenarios account for resource depletion over a period of a century and, due to the anticipated transition to higher-fuel-cost categories in the longer run, they shift to non-fossil energy sources much earlier than, for example, the IEA scenarios, especially for electricity supply. Consequently, the range for the shares of fossil-sourced power generation is between 43 and 58% for 2020, while the IEA projects a share of 71%. The corresponding sectoral shares in CO_2 emissions mirror the electricity generating mix: the IEA projects 43% for power generation (IEA, 2002) compared to a range of 28 to 32% in the six illustrative SRES scenarios.

Table 2.5 Carbon dioxide emissions from sectors in major world regions in six IPCC SRES scenarios in 2020 and 2050 (IPCC, 2000). Continued on next page.

A1B										
Sector	**Africa**	**CPA**	**EEFSU**	**LAM**	**Middle East**	**USA**	**P-OECD**	**S&EA**	**OECD West**	**Sector total**
Power	2,016	3,193	1,482	1,182	721	1,607	698	2,063	1,244	14,207
Industry	1,046	2,512	1,465	1,689	966	1,122	564	1,834	1,123	12,321
Res/Com	642	1,897	439	566	195	637	238	950	933	6,496
Transport	877	1,008	312	1,502	1,052	2,022	659	1,592	2,175	11,199
Region total	4,580	8,610	3,698	4,938	2,934	5,388	2,159	6,439	5,476	44,222

A1T	**Sub-Saharan**											
Sector	**Africa**	**CPA**	**E Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**	**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	333	2,165	356	705	396	368	2,470	448	1,388	195	1,221	10,045
Industry	358	2,840	208	727	885	465	690	292	954	748	530	8,699
Res/Com	730	2,773	105	352	713	149	771	150	795	690	627	7,855
Refineries	107	211	23	196	282	139	370	75	250	42	219	1,913
Synfuels	59	122	9	22	139	36	127	30	211	38	107	900
Hydrogen	57	145	26	80	57	61	231	74	75	47	177	1,030
Transport	435	1,235	96	578	1,159	837	2,394	450	620	432	1,448	9,684
Region total	2,078	9,491	823	2,661	3,631	2,055	7,053	1,519	4,292	2,192	4,330	40,126

A1FI											
Sector	**Africa**	**CPA**	**EEFSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**W. Europe**	**Sector total**
Power	427	3,732	2,248	680	370	2,618	181	753	2,546	1,640	15,195
Industry	622	3,498	1,121	695	426	1,418	153	416	1,530	1,384	11,262
Res/Com	135	1,363	582	125	25	755	102	115	488	786	4,477
Transport	456	542	588	977	297	2,210	168	357	1,357	1,345	8,297
Synfuels	10	12	126	2	0	52	3	12	2	21	238
Hydrogen	0	0	0	0	0	0	0	0	0	0	0
Fuel flared	21	11	19	135	74	9	1	1	52	4	327
Region total	1,670	9,159	4,682	2,613	1,192	7,062	608	1,654	5,976	5,181	39,796

Source: Total emissions $MtCO_2$ 2020

CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

Table 2.5 Continued.

A2													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	670	1,616	488	923	1,130	857	3,680	224	689	356	1,282	1,663	13,579
Industry	290	1,786	261	417	625	402	808	111	291	218	708	528	6,444
Res/Com	269	746	118	539	209	434	639	92	155	87	251	644	4,181
Transport	358	606	130	314	1,060	569	2,013	200	406	334	332	1,270	7,592
Others	394	439	112	371	644	538	567	68	247	269	142	532	4,324
Region total	1,981	5,193	1,109	2,563	3,668	2,800	7,706	696	1,788	1,264	2,715	4,638	36,120

B1													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	629	1,148	377	670	1,031	699	2,228	128	477	354	972	1,118	9,829
Industry	259	1,377	210	290	531	362	537	79	205	209	611	355	5,024
Res/Com	283	602	108	471	193	350	511	74	132	79	250	557	3,611
Transport	384	578	136	343	987	509	1,708	172	365	314	370	1,204	7,070
Others	392	413	99	291	591	502	481	55	169	266	164	432	3,856
Region total	1,946	4,118	931	2,064	3,333	2,422	5,466	506	1,348	1,222	2,367	3,665	29,389

B2	Sub-Saharan												
Sector	**Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**		**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	317	1,451	398	149	338	342	3,317		459	1,017	398	1,234	9,420
Industry	307	2,017	232	956	754	400	993		223	796	634	679	7,990
Res/Com	854	1,936	137	330	462	177	1,213		174	440	929	768	7,420
Refineries	70	241	42	169	223	193	480		98	242	111	271	2,139
Synfuels	30	18	2	32	47	16	126		4	77	12	56	420
Hydrogen	15	274	15	18	24	17	159		31	108	36	119	817
Transport	224	655	105	530	715	506	2,278		384	784	468	1,164	7,812
Region total	1,816	6,591	931	2,184	2,563	1,652	8,566		1,373	3,464	2,589	4,292	36,019

Source: Total emissions MtCO$_2$ 2020

CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

Table 2.5 Continued.

A1B										
Sector	**Africa**	**CPA**	**EEFSU**	**LAM**	**Middle East**	**USA**	**P-OECD**	**S&EA**	**OECD West**	**Sector total**
Power	4,078	2,708	1,276	1,165	840	1,361	588	2,700	1,459	16,174
Industry	2,304	2,555	1,645	2,384	1,635	969	395	3,273	1,038	16,199
Res/Com	2,610	3,297	879	1,074	415	797	236	2,056	1,004	12,369
Transport	4,190	2,082	512	2,841	2,676	2,091	690	4,506	2,278	21,867
Region total	13,182	10,643	4,311	7,465	5,566	5,218	1,909	12,535	5,779	66,609

A1T	**Sub-Sharan**											
Sector	**Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**	**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	925	3,831	119	203	788	958	606	107	1,039	745	147	9,469
Industry	1,871	983	77	299	433	614	420	104	521	1,394	278	6,996
Res/Com	774	2,574	70	448	1,576	598	878	116	1,154	1,285	507	9,979
Refineries	71	477	12	395	314	299	263	32	287	137	42	2,330
Synfuels	811	442	137	118	699	22	715	114	515	339	418	4,329
Hydrogen	290	99	37	364	0	647	0	0	151	256	612	2,456
Transport	1,083	4,319	280	1,121	2,106	1,613	2,094	386	1,839	1,545	1,464	17,851
Region total	5,825	12,725	732	2,949	5,917	4,751	4,977	859	5,506	5,702	3,468	53,411

A1FI											
Sector	**Africa**	**CPA**	**EEFSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**W. Europe**	**Sector total**
Power	4,413	7,598	4,102	2,604	1,409	3,485	240	918	9,530	2,374	36,673
Industry	2,022	4,899	1,066	948	857	1,295	118	337	2,731	1,244	15,517
Res/Com	503	2,093	814	238	70	854	95	112	1,172	854	6,805
Transport	2,680	1,207	1,031	2,173	860	2,753	176	418	4,525	1,516	17,340
Synfuels	259	2,629	2,189	35	0	1,021	50	171	267	418	7,039
Hydrogen	0	0	0	0	0	0	0	0	0	0	0
Fuel flared	50	26	43	102	40	13	3	1	20	6	305
Region total	9,927	18,453	9,246	6,099	3,236	9,421	682	1,958	18,246	6,412	83,679

Source: Total emissions $MtCO_2$ 2050
CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

Table 2.5 Continued.

A2													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	2,144	3,406	913	1,679	2,621	2,518	4,653	310	1,028	967	3,660	1,766	25,666
Industry	881	2,727	345	725	1,118	899	895	115	276	413	1,627	487	10,506
Res/Com	907	1,451	157	735	325	719	644	95	144	179	599	628	6,582
Transport	1,061	901	193	646	1,547	1,370	1,946	191	378	578	703	1,275	10,788
Others	719	643	106	452	754	904	582	67	142	304	359	429	5,461
Region total	5,713	9,127	1,714	4,237	6,365	6,409	8,719	778	1,967	2,441	6,949	4,585	59,003
B1													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	573	251	104	343	496	662	342	30	82	313	1,243	311	4,749
Industry	556	985	121	235	465	574	319	44	103	250	877	171	4,699
Res/Com	517	465	92	358	242	298	338	52	81	105	455	384	3,389
Transport	959	571	127	466	946	834	976	104	204	390	660	732	6,968
Others	414	280	45	209	378	458	230	29	60	198	253	225	2,779
Region total	3,019	2,551	488	1,612	2,527	2,825	2,205	259	529	1,255	3,488	1,824	22,584
B2	**Sub-Saharan**												
Sector	**Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**		**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	654	1,703	474	576	274	753	2,280		289	762	1,357	936	10,060
Industry	932	1,751	166	685	688	601	708		66	827	1,499	406	8,328
Res/Com	623	1,850	85	386	477	127	1,084		129	661	1,106	610	7,138
Refineries	43	360	14	409	200	85	382		47	244	262	112	2,157
Synfuels	453	139	56	285	326	448	174		50	223	54	97	2,304
Hydrogen	308	1,312	43	278	277	186	319		29	185	444	364	3,743
Transport	572	1,531	145	840	1,230	799	2,577		340	1,014	1,075	1,336	11,459
Region total	3,584	8,645	984	3,458	3,471	2,999	7,524		951	3,917	5,797	3,861	45,189

Source: Total emissions $MtCO_2$ 2050. Notes:

The division of the world into large economic regions differs between the various models underlying the SRES scenarios. Tables 2.5 and 2.6 consolidate the original model regions at a level that makes model results comparable (although the exact geographical coverage of the regions may vary).

CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

currently in operation around the world and those planned to be built in the near future was conducted, together with a review of industrial boilers in selected regions. Capture factors were established on the basis of installed capacity, fuel type, unit size, and other technical parameters. Outside the energy and industry sectors, there are only very limited prospects for practical CO_2 capture because sources in the residential sectors are small, dispersed, and often mobile, and contain only low concentrations. These factors result in lower capture factors.

In the assessment of CO_2 capture, perhaps the most important open question is what will happen in the transport sector over the next few decades. If the above average increases in energy use for transport projected by all models in all scenarios involve traditional fossil-fuelled engine technologies, the capture and storage of transport-related CO_2 will – though theoretically possible –remain technically meaningless (excess weight, on-board equipment, compression penalty, etc.). However, depending on the penetration rate of hydrogen-based transport technologies, it should be possible to retrofit CO_2-emitting hydrogen production facilities with CO_2 capture equipment. The transport sector provides a huge potential for indirect CO_2 capture but feasibility depends on future hydrogen production technologies.

CO_2 capture might also be technically feasible from biomass-fuelled power plants, biomass fermentation for alcohol production or units for the production of biomass-derived hydrogen. It is conceivable that these technologies might play a significant role by 2050 and produce negative emissions across the full technology chain.

The results of applying the capture factors developed by Toth and Rogner (2006) to the CO_2 emissions of the SRES scenarios of Table 2.5 are presented in Table 2.6. Depending on the scenario, between 30 and 60% of global power generation emissions could be suitable for capture by 2050 and 30 to 40% of industry emissions could also be captured in that time frame.

The technical potentials for CO_2 capture presented here are only the first step in the full carbon dioxide capture and storage chain. The variations across scenarios reflect the uncertainties inherently associated with scenario and modelling analyses. The ranges of the technical capture potential relative to total CO_2 emissions are 9–12% (or 2.6–4.9 $GtCO_2$) by 2020 and 21–45% (or 4.7–37.5 $GtCO_2$) by 2050.

2.4 Geographical relationship between sources and storage opportunities

The preceding sections in this chapter have described the geographical distributions of CO_2 emission sources. This section gives an overview of the geographic distribution of potential storage sites that are in relative proximity to present-day sites with large point sources.

2.4.1 Global storage opportunities

Global assessments of storage opportunities for CO_2 emissions involving large volumes of CO_2 storage have focused on the options of geological storage or ocean storage, where CO_2 is:

- injected and trapped within geological formations at subsurface depths greater than 800 m where the CO_2 will be supercritical and in a dense liquid-like form in a geological reservoir, or
- injected into deep ocean waters with the aim of dispersing it quickly or depositing it at great depths on the floor of the ocean with the aim of forming CO_2 lakes.

High-level global assessments of both geological and ocean storage scenarios have estimated that there is considerable capacity for CO_2 storage (the estimates range from hundreds to tens of thousands of $GtCO_2$). The estimates in the literature of storage capacity in geological formations and in the oceans are discussed in detail in Chapters 5 and 6 respectively and are not discussed further in this chapter.

2.4.2 Consideration of spatial and temporal relationships

As discussed in Chapter 5, the aim of geological storage is to replicate the natural occurrence of deep subsurface fluids, where they have been trapped for tens or hundreds of millions of years. Due to the slow migration rates of subsurface fluids observed in nature (often centimetres per year), and even including scenarios where CO_2 leakage to the surface might unexpectedly occur, CO_2 injected into the geological subsurface will essentially remain geographically close to the location where it is injected. Chapter 6 shows that CO_2 injected into the ocean water column does not remain in a static location, but will migrate at relatively rapid speed throughout the ocean as dissolved CO_2 within the prevailing circulation of ocean currents. So dissolved CO_2 in the water column will not remain where it is injected in the immediate short term (i.e., a few years to some centuries). Deep-ocean lakes of CO_2 will, in principle, be more static geographically but will dissolve into the water column over the course of a few years or centuries.

These spatial and temporal characteristics of CO_2 migration in geological and ocean storage are important criteria when attempting to make maps of source and storage locations. In both storage scenarios, the possibility of adjoining storage locations in the future and of any possible reciprocal impacts will need to be considered.

2.4.3 Global geographical mapping of source/storage locations

To appreciate the relevance of a map showing the geographic distribution of sources and potential storage locations, it is necessary to know the volumes of CO_2 emissions and the storage capacity that might be available, and to establish a picture of the types and levels of technical uncertainty associated with the

Table 2.6 CO_2 emissions available for capture and storage in 2020 and 2050 from sectors in major world regions under six IPCC SRES scenarios (after Toth and Rogner, 2005). Continued on next page.

Potential CO_2 capture in $MtCO_2$ 2020													
A1B													
Sector	**Africa**	**CPA**	**EEFSU**		**LAM**	**MEA**	**NAM**		**P-OECD**	**S&EA**		**OECD West**	**Sector total**
Power	117	475	319		165	167	479		185	290		351	2,548
Industry	33	182	168		155	127	156		64	130		159	1,173
Res/Com	6	46	21		16	7	30		12	17		51	207
Transport	0	0	0		0	0	0		0	0		0	0
Region total	156	702	508		337	301	665		261	437		561	3,928
A1T	**Sub-Saharan**												
Sector	**Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**		**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	21	334	78	139	39	110	715		128	164	20	366	2,115
Industry	6	195	18	70	56	57	85		21	35	57	65	664
Res/Com	4	59	4	16	14	4	37		7	12	6	36	200
Refineries	22	54	6	50	71	42	113		23	63	11	67	521
Synfuels	30	74	6	16	85	25	91		23	86	16	81	532
Hydrogen	46	125	24	73	50	56	211		68	65	41	162	919
Transport	0	0	0	0	0	0	0		0	0	0	0	0
Region total	129	840	135	364	315	294	1,251		270	426	150	777	4,950
A1FI													
Sector	**Africa**	**CPA**	**EEFSU**		**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**		**W. Europe**	**Sector total**
Power	30	607	525		95	90	791	55	226	401		500	3,319
Industry	15	259	144		49	58	189	22	51	104		198	1,091
Res/Com	1	31	26		4	1	36	4	6	7		48	165
Transport	0	0	0		0	0	0	0	0	0		0	0
Synfuels	5	7	89		1	0	37	2	9	1		16	167
Hydrogen	0	0	0		0	0	0	0	0	0		0	0
Fuel flared	0	0	0		0	0	0	0	0	0		0	0
Region total	50	904	785		149	149	1,053	83	292	513		763	4,741

CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

Table 2.6 Continued.

	Potential CO_2 capture in $MtCO_2$ 2020												
A2													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	41	241	102	217	150	208	1,111	66	201	60	140	477	3,016
Industry	8	127	26	49	42	48	111	15	35	12	49	68	590
Res/Com	3	25	5	26	6	15	30	4	8	2	5	35	163
Transport	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	0	0	0	0	0	0	0	0	0	0	0	0	0
Region total	51	392	134	292	198	271	1,252	86	244	74	194	579	3,769
B1													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	38	156	81	160	147	174	632	35	126	57	129	304	2,040
Industry	6	79	19	32	35	43	68	10	22	10	45	43	411
Res/Com	3	22	5	22	5	11	22	3	6	2	5	28	134
Transport	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	0	0	0	0	0	0	0	0	0	0	0	0	0
Region total	47	256	105	214	187	228	722	49	155	69	179	375	2,584
B2	**Sub-Saharan**												
Sector	**Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**		**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	18	225	82	24	52	100	982		114	153	41	349	2,140
Industry	5	122	19	89	42	50	103		12	19	30	73	565
Res/Com	5	42	5	15	6	4	46		8	6	6	35	178
Refineries	14	60	11	42	56	58	144		29	61	28	81	583
Synfuels	15	11	2	22	28	11	88		3	31	5	42	258
Hydrogen	12	233	14	16	20	16	144		28	92	31	107	712
Transport	0	0	0	0	0	0	0		0	0	0	0	0
Region total	69	693	132	209	204	239	1,507		196	361	140	687	4,437

CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

Table 2.6 Continued.

	Potential CO_2 Capture in $MtCO_2$ 2050												
A1B													
Sector	**Africa**	**CPA**	**EEFSU**		**LAM**	**Middle East**	**NAM**		**P-OECD**	**S&EA**		**OECD West**	**Sector total**
Power	2,167	1,701	831		674	548	1,015		438	1,658		1,092	10,124
Industry	760	931	726		1,015	701	439		165	1,201		481	6,419
Res/Com	222	660	191		128	87	172		68	393		319	2,241
Transport	0	0	0		0	0	0		0	0		0	0
Region total	3,149	3,291	1,747		1,818	1,337	1,627		671	3,253		1,892	18,783
A1T	**Sub-Saharan**												
Sector	**Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**		**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	526	2,530	90	127	469	753	477		84	702	423	115	6,296
Industry	329	307	25	110	165	191	139		33	111	288	102	1,799
Res/Com	66	445	16	94	189	126	190		32	238	140	159	1,694
Refineries	37	367	9	304	242	245	216		26	221	98	35	1,799
Synfuels	665	407	126	109	645	20	660		105	449	296	386	3,867
Hydrogen	283	96	36	354	0	630	0		0	147	249	596	2,392
Transport	0	0	0	0	0	0	0		0	0	0	0	0
Region total	1,905	4,154	301	1,098	1,709	1,965	1,681		280	1,867	1,493	1,393	17,846
A1FI													
Sector	**Africa**	**CPA**	**EEFSU**		**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**		**W. Europe**	**Sector total**
Power	2,369	4,836	2,691		1,486	992	2,677	186	705	5,979		1,862	23,781
Industry	557	1,817	462		332	370	559	53	144	962		569	5,826
Res/Com	37	430	188		27	15	189	23	30	229		279	1,448
Transport	0	0	0		0	0	0	0	0	0		0	0
Synfuels	213	2,425	2,019		32	0	942	46	158	233		385	6,453
Hydrogen	0	0	0		0	0	0	0	0	0		0	0
Fuel flared	0	0	0		0	0	0	0	0	0		0	0
Region total	3,175	9,509	5,360		1,877	1,377	4,367	308	1,038	7,403		3,095	37,508

CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

Table 2.6 Continued.

Potential CO_2 Capture in $MtCO_2$ 2050													
A2													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	1,158	2,080	571	1,110	1,407	1,628	3,569	230	779	631	1,912	1,284	16,359
Industry	257	991	128	286	365	319	384	46	112	139	519	194	3,741
Res/Com	78	293	34	155	41	148	143	21	42	30	113	197	1,295
Transport	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	0	0	0	0	0	0	0	0	0	0	0	0	0
Region total	1,493	3,365	733	1,552	1,812	2,095	4,096	298	933	799	2,544	1,675	21,394
B1													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	266	130	63	218	258	418	221	19	52	185	635	203	2,668
Industry	138	268	40	83	137	196	118	16	36	72	271	64	1,437
Res/Com	44	80	19	69	28	57	69	11	21	16	73	111	598
Transport	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	0	0	0	0	0	0	0	0	0	0	0	0	0
Region total	447	478	121	371	423	671	408	46	110	273	980	377	4,703
B2	**Sub-Saharan**												
Sector	**Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**		**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	339	1,067	307	345	164	563	1,710		216	439	673	704	6,526
Industry	166	459	63	248	266	257	225		20	157	238	144	2,243
Res/Com	42	309	18	77	52	16	224		35	102	104	182	1,161
Refineries	22	270	11	306	150	68	305		38	183	183	89	1,625
Synfuels	362	125	51	256	293	403	157		45	189	46	87	2,015
Hydrogen	293	1,246	41	264	263	176	303		27	176	421	345	3,556
Transport	0	0	0	0	0	0	0		0	0	0	0	0
Region total	1,223	3,476	489	1,496	1,187	1,484	2,924		383	1,246	1,665	1,552	17,125

Notes: The division of the world into large economic regions differs in the different models underlying the SRES scenarios. Tables 2.5 and 2.6 consolidate the original model regions at a level that makes model results comparable (although the exact geographical coverage of the regions may vary).
CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

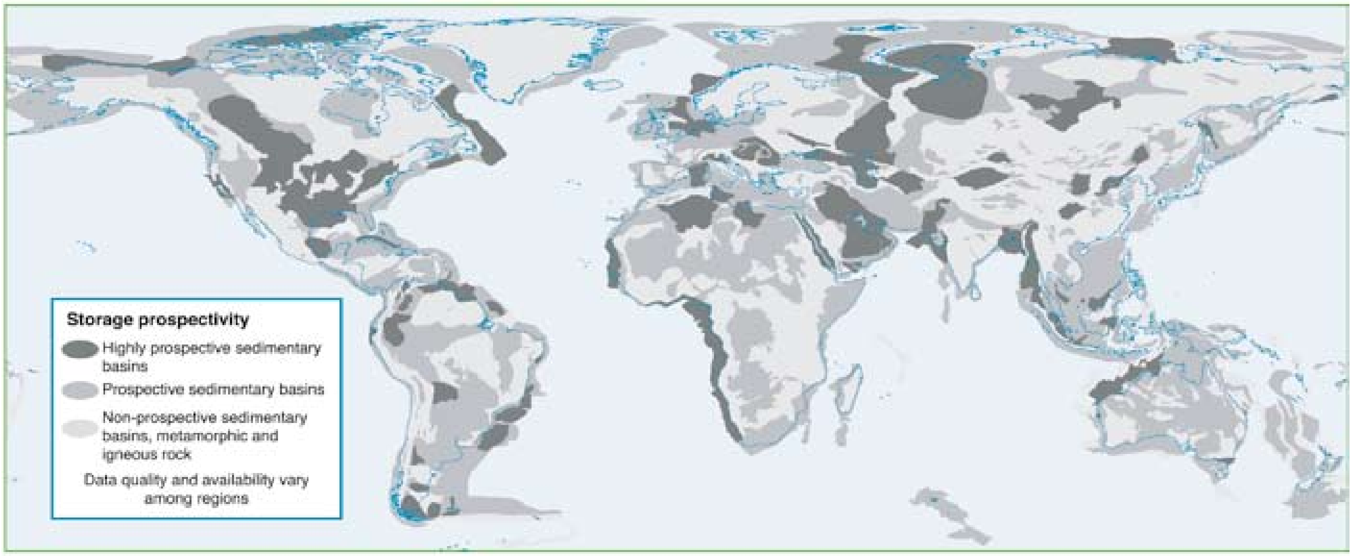

Figure 2.4 Prospective areas in sedimentary basins where suitable saline formations, oil or gas fields, or coal beds may be found. Locations for storage in coal beds are only partly included. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present in a given area based on the available information. This figure should be taken as a guide only, because it is based on partial data, the quality of which may vary from region to region, and which may change over time and with new information (Bradshaw and Dance, 2004).

storage sites that will affect their viability as potential solutions. As indicated above in this chapter, there are some 7,500 large stationary sources with emissions in excess of 0.1 $MtCO_2$ yr^{-1} and that number is projected to rise by 2050. The mapping does not take into account the 'capture factors' presented in Section 2.3.2.

2.4.3.1 Geological storage and source location matching

Chapter 5 includes detailed discussions of the geological characteristics of storage sites. Before discussing the global locations for geological storage opportunities, it is necessary to describe some basic fundamentals of geological storage. The world's geological provinces can be allocated to a variety of rock types, but the main ones relevant to geological storage are sedimentary basins that have undergone only minor tectonic deformation and are at least 1000 m thick with adequate reservoir/seal pairs to allow for the injection and trapping of CO_2. The petroleum provinces of the world are a subset of the sedimentary basins described above, and are considered to be promising locations for the geological storage of CO_2 (Bradshaw *et al*., 2002). These basins have adequate reservoir/seal pairs, and suitable traps for hydrocarbons, whether liquids or gases. The remaining geological provinces of the world can generally be categorized as igneous (rocks formed from crystallization of molten liquid) and metamorphic (pre-existing rocks formed by chemical and physical alteration under the influence of heat, pressure and chemically active fluids) provinces. These rock types are commonly known as hard-rock provinces, and they will not be favourable for CO_2 storage as they are generally not porous and permeable and will therefore not readily transmit fluids. More details on the suitability of sedimentary basins and characterization of specific sites are provided in Chapter 5.

Figure 2.4 shows the 'prospectivity'(see Annex II) of various parts of the world for the geological storage of CO_2. Prospectivity is a term commonly used in explorations for any geological resource, and in this case it applies to CO_2 storage space. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present in a given area based on the available information. By nature, it will change over time and with new information. Estimates of prospectivity are developed by examining data (if possible), examining existing knowledge, applying established conceptual models and, ideally, generating new conceptual models or applying an analogue from a neighbouring basin or some other geologically similar setting. The concept of prospectivity is often used when it is too complex or technically impossible to assign numerical estimates to the extent of a resource.

Figure 2.4 shows the world's geological provinces broken down into provinces that are thought, at a very simplistic level, to have CO_2 storage potential that is either: 1) highly prospective, 2) prospective, or 3) non-prospective (Bradshaw and Dance, 2004). Areas of high prospectivity are considered to include those basins that are world-class petroleum basins, meaning that they are the basins of the world that are producing substantial volumes of hydrocarbons. It also includes areas that are expected to have substantial storage potential. Areas of prospective storage potential are basins that are minor petroleum basins but not world-class, as well as other sedimentary basins that have not been highly deformed. Some of these basins will be highly prospective for CO_2 storage and others will have low prospectivity.

Determining the degree of suitability of any of these basins for CO_2 storage will depend on detailed work in each area. Areas that are non-prospective are highly deformed sedimentary basins and other geological provinces, mainly containing metamorphic and igneous rocks. Some of these

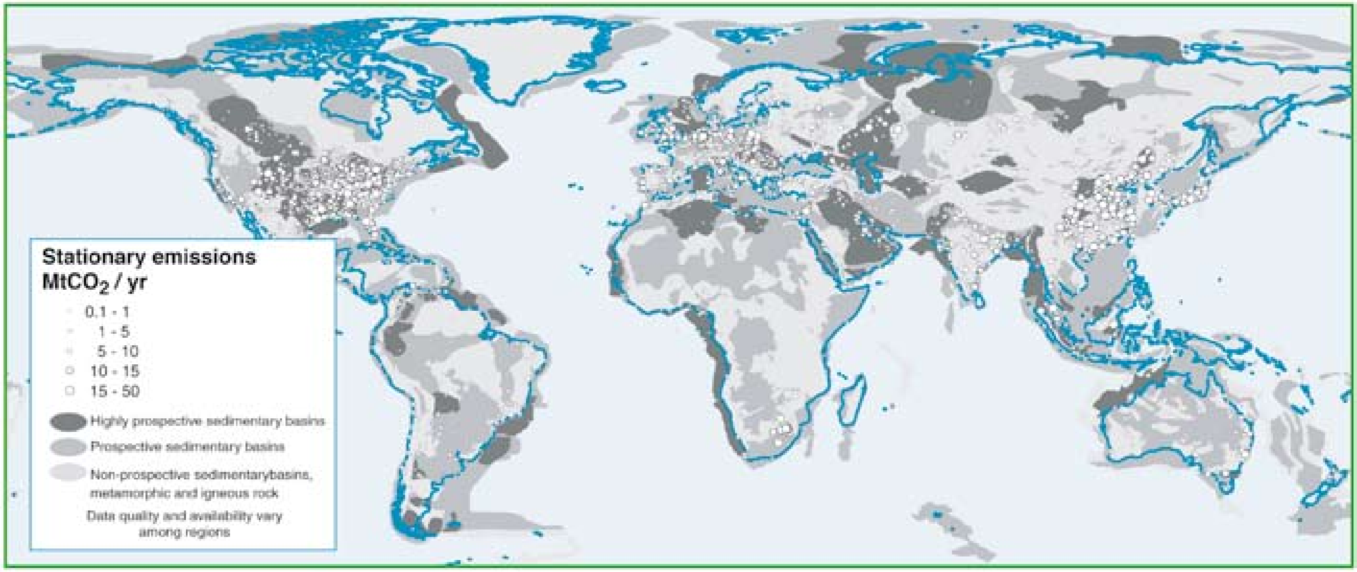

Figure 2.5 Geographical relationship between CO_2 emission sources and prospective geological storage sites. The dots indicate CO_2 emission sources of 0.1–50 $MtCO_2$ yr^{-1}. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present in a given area based on the available information. This figure should be taken as a guide only, because it is based on partial data, the quality of which may vary from region to region, and which may change over time and with new information.

provinces might have some local niche opportunities for CO_2 storage, but at this stage they would not be considered suitable for a conventional form of CO_2 storage. As Bradshaw and Dance (2004) explain, this map is subject to significant caveats and based on significant assumptions because of the data source from which it was generated. However, it can be used as a general (although not specific) guide at the global scale to the location of areas that are likely to provide opportunities for the geological storage of CO_2. Due to the generalized manner in which this map has been created, and the lack of specific or hard data for each of the basins assessed, the 'prospectivity' levels assigned to each category have no meaningful correlative statistical or probabilistic connotation. To achieve a numerical analysis of risk or certainty would require specific information about each and every basin assessed.

Figure 2.5 shows the overlap of the sedimentary basins that are prospective for CO_2 storage potential with the current locations of large sources of stationary emissions (IEA GHG, 2002a). The map can be simplistically interpreted to identify areas where large distances might be required to transport emissions from any given source to a geological storage location. It clearly shows areas with local geological storage potential and low numbers of emission sites (for example, South America) as well as areas with high numbers of emission sites and few geological storage options in the vicinity (the Indian sub-continent, for example). This map, however, does not address the relative capacity of any of the given sites to match either large emission sources or small storage capacities. Neither does it address any of the technical uncertainties that could exist at any of the storage sites, or the cost implications for the emission sources of the nature of the emission plant or the purity of the emission sources. Such issues of detailed source-to-store matching are dealt with in Chapter 5.

Figures 2.6, 2.7 and 2.8 show the regional emission clusters for twelve regions of the world and the available storage opportunities within each region. They also compare the relative ranking of the area of available prospective sedimentary basins in a 300 km radius around emission clusters (Bradshaw and Dance, 2004). The 300 km radius was selected because it was considered useful as an indicator of likely transport distances for potentially viable source-to-storage matches (see Chapter 5). Although this data could suggest trends, such as high emissions for China with a small area of prospective sedimentary basins, or a large area of prospective sedimentary basins with low emissions for the Middle East, it is premature to make too many assumptions until detailed assessments are made in each region as to the quality and viability of each sedimentary basin and specific proposed sites. Each basin will have its own technical peculiarities, and because the science of injection and storage of very large volumes of CO_2 is still developing, it is premature at this stage to make any substantive comments about the viability of individual sedimentary basins unless there are detailed data sets and assessments (see Chapter 5). These maps do, however, indicate where such detailed geological assessments will be required – China and India, for example – before a comprehensive assessment can be made of the likely worldwide impact of the geological storage of CO_2. These maps also show that CO_2 storage space is a resource, just like any other resource; some regions will have many favourable opportunities, and others will not be so well-endowed (Bradshaw and Dance, 2004).

Figure 2.9 shows those emission sources with high concentrations (>95%) of CO_2, with their proximity to prospective geological storage sites. Clusters of high-concentration sources can be observed in China and North America and to lesser extent in Europe.

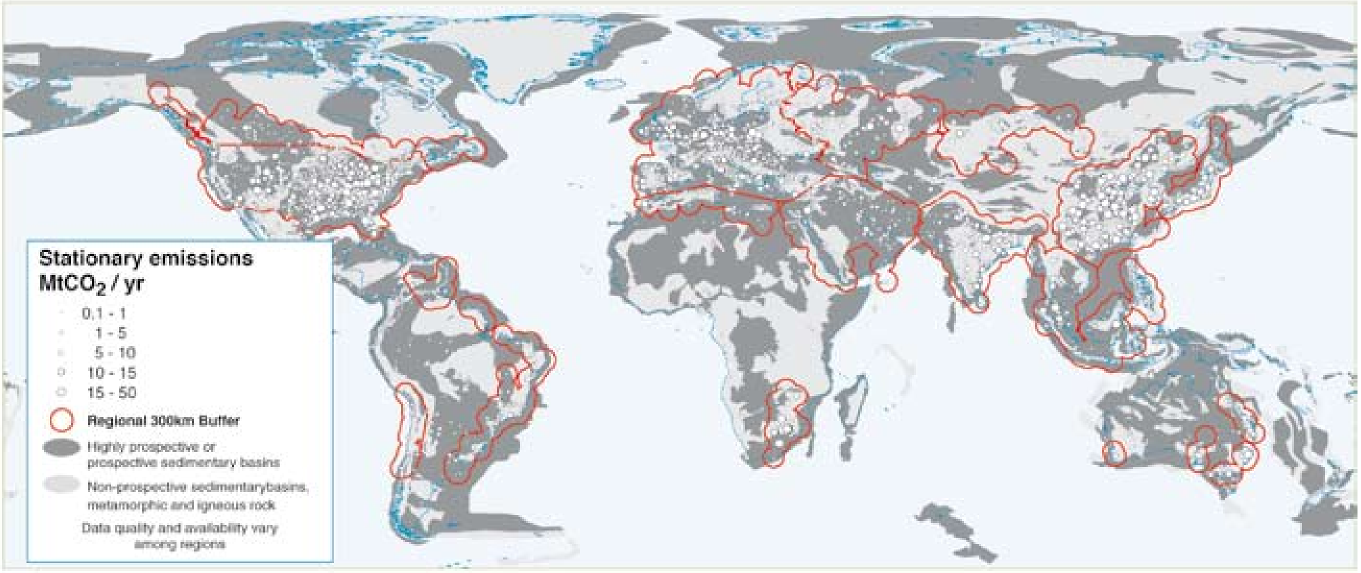

Figure 2.6 Regional emission clusters with a 300 km buffer relative to world geological storage prospectivity (Bradshaw and Dance, 2004).

2.4.3.2 Ocean storage and source-location matching

Due to a lack of publicly available literature, a review of the proximity of large CO_2 point sources and their geographical relationship to ocean storage opportunities on the global scale could not be undertaken. A related study was undertaken that analysed seawater scrubbing of CO_2 from power stations along the coastlines of the world. The study considered the number of large stationary sources (in this case, power generation plants) on the coastlines of the worldwide that are located within 100 km of the 1500 m ocean floor contour (IEA GHG, 2000a). Eighty-nine potential power generation sources were identified that were close to these deep-water locations. This number represents only a small proportion (< 2%) of the total number of large stationary sources in the power generation

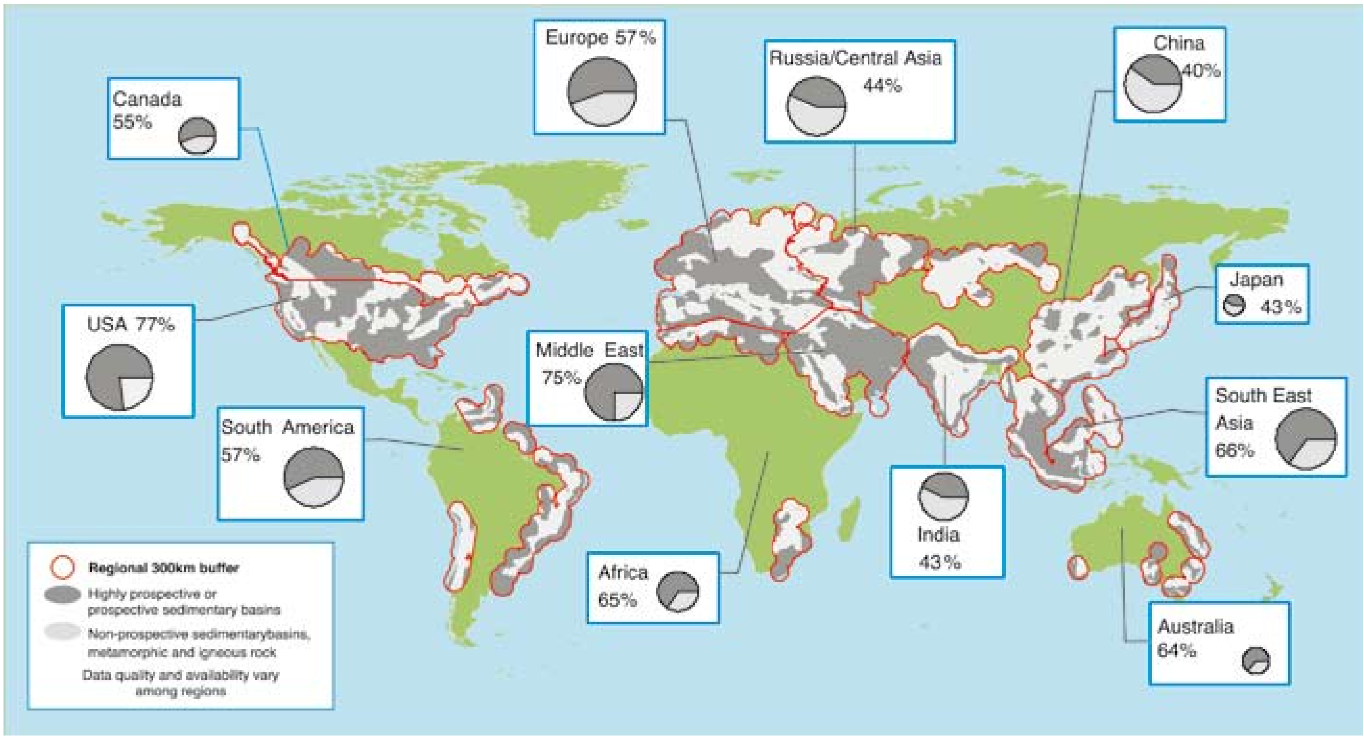

Figure 2.7 Regional storage opportunities determined by using a ratio (percentage) of all prospective areas to non-prospective areas within a 300 km buffer around major stationary emissions. The pie charts show the proportion of the prospective areas (sedimentary basins) in the buffer regions (Bradshaw and Dance, 2004).

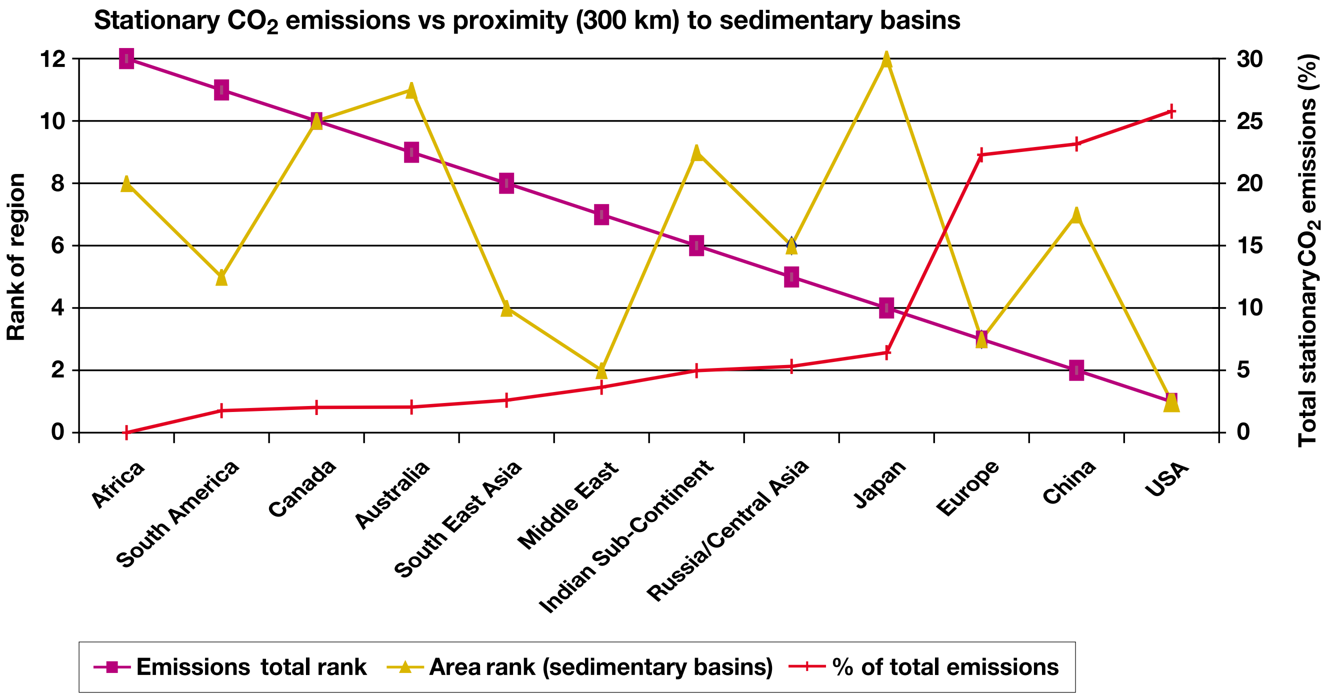

Figure 2.8 Proximity of emissions to sedimentary basins.

sector worldwide (see Section 2.1). A larger proportion of power plants could possibly turn to deep-ocean storage because transport over distances larger than 100 km may prove cost-effective in some cases; nevertheless, this study indicates that a higher fraction of large stationary sources could be more cost-effectively matched to geological storage reservoirs than ocean storage sites. There are many issues that will also need to be addressed when considering deep-ocean storage sites, including jurisdictional boundaries, site suitability, and environmental impact etc., which are discussed in Chapter 6. The spatial and temporal nature of ocean water-column injection may affect the approach to source and storage matching, as the CO_2 will not remain adjacent to the local region where the CO_2 is injected, and conceivably might migrate across jurisdictional boundaries and into sensitive environmental provinces.

2.5 Alternative energy carriers and CO_2 source implications

As discussed earlier in this chapter, a significant fraction of the world's CO_2 emissions comes from transport, residences, and other small, distributed combustion sources. Whilst it is

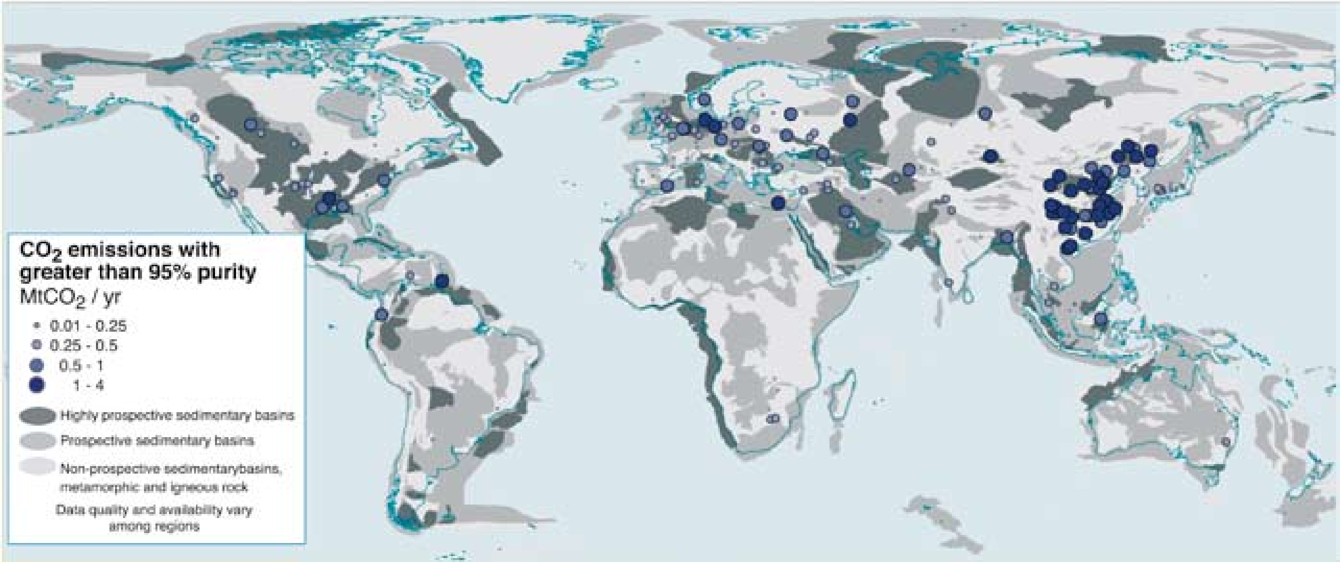

Figure 2.9 Geographical proximity of high-concentration CO_2 emission sources (> 95%) to prospective geological storage sites.

currently not economically feasible to capture and store CO_2 from these small, distributed sources, these emissions could be reduced if the fossil fuels used in these units were replaced with either:

- carbon-free energy carriers (e.g. electricity or hydrogen);
- energy carriers that are less carbon-intensive than conventional hydrocarbon fuels (e.g., methanol, Fischer-Tropsch liquids or dimethyl ether);
- biomass energy that can either be used directly or to produce energy carriers like bioethanol. If the biomass is grown sustainably the energy produced can be considered carbon-neutral.

In the first two cases, the alternative energy carriers can be produced in centralized plants that incorporate CO_2 capture and storage. In the case of biomass, CO_2 capture and storage can also be incorporated into the energy carrier production schemes. The aim of this section is to explore the implications that introducing such alternative energy carriers and energy sources might have for future large point sources of CO_2 emissions.

2.5.1 Carbon-free energy carriers

2.5.1.1 Electricity

The long-term trend has been towards the electrification of the energy economy, and this trend is expected to continue (IPCC, 2000). To the extent that expanded electricity use is a substitute for the direct use of fossil fuels (e.g., in transport, or for cooking or heating applications in households), the result can be less CO_2 emissions if the electricity is from carbon-free primary energy sources (renewable or nuclear) or from distributed generators such as fuel cells powered by hydrogen produced with near-zero fuel-cycle-wide emissions or from large fossil-fuel power plants at which CO_2 is captured and stored.

While, in principle, all energy could be provided by electricity, most energy projections envision that the direct use of fuels will be preferred for many applications (IPCC, 2000). In transport, for example, despite intensive developmental efforts, battery-powered electric vehicles have not evolved beyond niche markets because the challenges of high cost, heavy weight, and long recharging times have not been overcome. Whilst the prospects of current hybrid electric vehicles (which combine fossil fuel and electric batteries) penetrating mass markets seem good, these vehicles do not require charging from centralized electrical grids. The successful development of 'plug-in hybrids' might lead to an expanded role for electricity in transport but such vehicles would still require fuel as well as grid electricity. In summary, it is expected that, although electricity's share of total energy might continue to grow, most growth in large point sources of CO_2 emissions will be the result of increased primary energy demand.

2.5.1.2 Hydrogen

If hydrogen can be successfully established in the market as an energy carrier, a consequence could be the emergence of large new concentrated sources of CO_2 if the hydrogen is manufactured from fossil fuels in large pre-combustion decarbonization plants with CO_2 capture and storage. Such plants produce a high concentration source of CO_2 (see Chapter 3 for details on system design). Where fossil fuel costs are low and CO_2 capture and storage is feasible, hydrogen manufactured in this way is likely to be less costly than hydrogen produced from renewable or nuclear primary energy sources (Williams, 2003; NRC, 2004). It should be noted that this technology can be utilized only if production sites are within a couple of hundred kilometres of where the hydrogen will be used, since cost-effective, long-distance hydrogen transport represents a significant challenge. Producing hydrogen from fossil fuels could be a step in technological development towards a hydrogen economy based on carbon-free primary energy sources through the establishment of a hydrogen utilization infrastructure (Simbeck, 2003).

Energy market applications for hydrogen include its conversion to electricity electrochemically (in fuel cells) and in combustion applications. Substituting hydrogen for fossil fuel burning eliminates CO_2 emissions at the point of energy use. Much of the interest in hydrogen market development has focused on distributed stationary applications in buildings and on transport. Fuel cells are one option for use in stationary distributed energy systems at scales as small as apartment buildings and even single-family residences (Lloyd, 1999). In building applications, hydrogen could also be combusted for heating and cooking (Ogden and Williams, 1989). In the transport sector, the hydrogen fuel cell car is the focus of intense development activity, with commercialization targeted for the middle of the next decade by several major automobile manufacturers (Burns *et al*., 2002). The main technological obstacles to the widespread use of fuel cell vehicles are the current high costs of the vehicles themselves and the bulkiness of compressed gaseous hydrogen storage (the only fully proven hydrogen storage technology), which restricts the range between refuelling (NRC, 2004). However, the currently achievable ranges might be acceptable to many consumers, even without storage technology breakthroughs (Ogden *et al*., 2004).

Hydrogen might also be used in internal combustion engine vehicles before fuel cell vehicles become available (Owen and Gordon, 2002), although efficiencies are likely to be less than with fuel cells. In this case, the range between refuelling would also be less than for hydrogen fuel cell vehicles with the same performance (Ogden et al., 2004). For power generation applications, gas turbines originally designed for natural gas operation can be re-engineered to operate on hydrogen (Chiesa *et al*., 2003).

Currently, there are a number of obstacles on the path to a hydrogen economy. They are: the absence of cost-competitive fuel cells and other hydrogen equipment and the absence of an infrastructure for getting hydrogen to consumers. These challenges are being addressed in many hydrogen R&D programmes and policy studies being carried out around the world (Sperling and Cannon, 2004). There are also safety concerns because, compared to other fuels, hydrogen has a wide flammability and detonation range, low ignition energy, and high flame speed. However, industrial experience shows that hydrogen can be manufactured and used safely in many applications (NRC, 2004).

There is widespread industrial experience with the production and distribution of hydrogen, mainly for the synthesis of ammonia fertilizer and hydro-treatment in oil refineries. Current global hydrogen production is 45 million t yr^{-1}, the equivalent to 1.4% of global primary energy use in 2000 (Simbeck, 2003). Forty-eight per cent is produced from natural gas, 30% from oil, 18% from coal, and 4% via electrolysis of water. Ammonia production, which consumes about 100,000 MW_t of hydrogen, is growing by 2–4% per year. Oil refinery demand for hydrogen is also increasing, largely because of the ongoing shift to heavier crude oils and regulations limiting the sulphur content of transport fuels. Most hydrogen is currently manufactured via steam methane reforming (SMR), steam reforming of naphtha, and the gasification of petroleum residues and coal. The SMR option is generally favoured due to its lower capital cost wherever natural gas is available at reasonable prices. Nevertheless, there are currently about 75 modern commercial gasification plants making about 20,000 MW_t of hydrogen from coal and oil refinery residues (NETL-DOE, 2002); these are mostly ammonia fertilizer plants and hydrogen plants in oil refineries in China, Europe, and North America. There are currently over 16,000 km of hydrogen pipelines around the world. Most are relatively short and located in industrial areas for large customers who make chemicals, reduce metals, and engage in the hydro-treatment of oil at refineries. The longest pipeline currently in operation is 400 km long and is located in a densely populated area of Europe, running from Antwerp to northern France. The pipeline operates at a pressure of about 60 atmospheres (Simbeck, 2004).

Fossil fuel plants producing hydrogen with CO_2 capture and storage would typically be large, producing volumes of the order of 1000 MW_t (720 t day^{-1})[6] in order to keep the hydrogen costs and CO_2 storage costs low. Per kg of hydrogen, the co-production rate would be about 8 $kgCO_2$ with SMR and 15 $kgCO_2$ with coal gasification, so that the CO_2 storage rates (for plants operated at 80% average capacity factor) would be 1.7 and 3.1 million tonnes per year for SMR and coal gasification plants respectively.

Making hydrogen from fossil fuels with CO_2 capture and storage in a relatively small number of large plants for use in large numbers of mobile and stationary distributed applications could lead to major reductions in fuel-cycle-wide emissions compared to petroleum-based energy systems. This takes into account all fossil fuel energy inputs, including energy for petroleum refining and hydrogen compression at refuelling stations (NRC, 2004; Ogden *et al.*, 2004). No estimates have yet been made of the number of large stationary, concentrated CO_2 sources that could be generated via such hydrogen production systems and their geographical distribution.

2.5.2 *Alternative energy carriers and CO_2 source implications*

Interest in synthetic liquid fuels stems from concerns about both the security of oil supplies (TFEST, 2004) and the expectation that it could possibly be decades before hydrogen can make a major contribution to the energy economy (NRC, 2004).

There is considerable activity worldwide relating to the manufacture of Fischer-Tropsch liquids from stranded natural gas supplies. The first major gas to liquids plant, producing 12,500 barrels per day, was built in Malaysia in 1993. Several projects are underway to make Fischer-Tropsch liquid fuels from natural gas in Qatar at plant capacities ranging from 30,000 to 140,000 barrels per day. Although gas to liquids projects do not typically produce concentrated by-product streams of CO_2, synthetic fuel projects using synthesis gas derived from coal (or other solid feedstocks such as biomass or petroleum residuals) via gasification could produce large streams of concentrated CO_2 that are good candidates for capture and storage. At Sasol in South Africa, coal containing some 20 million tonnes of carbon is consumed annually in the manufacture of synthetic fuels and chemicals. About 32% of the carbon ends up in the products, 40% is vented as CO_2 in dilute streams, and 28% is released as nearly pure CO_2 at a rate of about 20 million tonnes of CO_2 per year. In addition, since 2000, 1.5 million tonnes per year of CO_2 by-product from synthetic methane production at a coal gasification plant in North Dakota (United States) have been captured and transported 300 km by pipeline to the Weyburn oil field in Saskatchewan (Canada), where it is used for enhanced oil recovery (see Chapter 5 for more details). Coal-based synthetic fuel plants being planned or considered in China include six 600,000 t yr^{-1} methanol plants, two 800,000 t yr^{-1} dimethyl ether plants, and two or more large Fischer-Tropsch liquids plants[7]. In the United States, the Department of Energy is supporting a demonstration project in Pennsylvania to make 5,000 barrels/day of Fischer-Tropsch liquids plus 41 MW_e of electricity from low-quality coal.

If synthesis-gas-based energy systems become established in the market, economic considerations are likely to lead, as in the case of hydrogen production, to the construction of large facilities that would generate huge, relatively pure, CO_2 co-product streams. Polygeneration plants, for example plants that could produce synthetic liquid fuels plus electricity, would benefit as a result of economies of scale, economies of scope, and opportunities afforded by greater system operating flexibility (Williams *et al.*, 2000; Bechtel *et al.*, 2003; Larson and Ren, 2003; Celik *et al.*, 2005). In such plants, CO_2 could be captured from shifted synthesis gas streams both upstream and downstream of the synthesis reactor where the synthetic fuel is produced.

With CO_2 capture and storage, the fuel-cycle-wide greenhouse gas emissions per GJ for coal derived synthetic

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[6] A plant of this kind operating at 80% capacity could support 2 million hydrogen fuel cell cars with a gasoline-equivalent fuel economy of 2.9 L per 100 km driving 14,000 km per year.

[7] Most of the methanol would be used for making chemicals and for subsequent conversion to dimethyl ether, although some methanol will be used for transport fuel. The dimethyl ether would be used mainly as a cooking fuel.

fuels can sometimes be less than for crude oil-derived fuels. For example, a study of dimethyl ether manufacture from coal with CO_2 capture and storage found that fuel-cycle-wide greenhouse gas emissions per GJ ranged from 75 to 97% of the emission rate for diesel derived from crude oil, depending on the extent of CO_2 capture (Celik *et al.*, 2005).

The CO_2 source implications of making synthetic low-carbon liquid energy carriers with CO_2 capture and storage are similar to those for making hydrogen from fossil fuels: large quantities of concentrated CO_2 would be available for capture at point sources. Again, no estimates have yet been made of the number of large stationary sources that could be generated or of their geographical distribution.

2.5.3 CO_2 source implications of biomass energy production

There is considerable interest in some regions of the world in the use of biomass to produce energy, either in dedicated plants or in combination with fossil fuels. One set of options with potentially significant but currently uncertain implications for future CO_2 sources is bioenergy with CO_2 capture and storage. Such systems could potentially achieve negative CO_2 emissions. The perceived CO_2 emission benefits and costs of such systems are discussed elsewhere in this report (see Chapters 3 and 8) and are not discussed further here. The aim of this section is to assess the current scale of emissions from biomass energy production, to consider how they might vary in the future, and therefore to consider their impact on the future number, and scale, of CO_2 emission sources.

2.5.3.1 Bioethanol production

Bioethanol is the main biofuel being produced today. Currently, the two largest producers of bioethanol are the USA and Brazil. The USA produced 11 billion litres in 2003, nearly double the capacity in 1995. Production is expected to continue to rise because of government incentives. Brazilian production was over 14 billion litres per year in 2003/2004, similar to the level in 1997/1998 (Möllersten *et al.*, 2003). Bioethanol is used directly in internal combustion engines, without modification, as a partial replacement for petroleum-based fuels (the level of replacement in Europe and the USA is 5 to 10%).

Bioethanol plants are a high-concentration source of CO_2 at atmospheric pressure that can be captured and subsequently stored. As can be seen in Table 2.3, the numbers of these plants are significant in the context of high-purity sources, although their global distribution is restricted. These sources are comparable in size to those from ethylene oxide plants but smaller than those from ammonia plants.

Although the trend in manufacture is towards larger production facilities, the scale of future production will be determined by issues such as improvements in biomass production and conversion technologies, competition with other land use, water demand, markets for by-product streams and competition with other transport fuels.

On the basis of the literature currently available, it is not possible to estimate the number of bioethanol plants that will be built in the future or the likely size of their CO_2 emissions.

2.5.3.2 Biomass as a primary energy source

A key issue posed by biomass energy production, both with and without CO_2 capture and storage, is that of size. Current biomass energy production plants are much smaller than fossil fuel power plants; typical plant capacities are about 30 MW_e, with CO_2 emissions of less than 0.2 $MtCO_2$ per year. The size of these biomass energy production plants reflects the availability and dispersed nature of current biomass supplies, which are mainly crop and forestry residues.

The prospects for biomass energy production with CO_2 capture and storage might be improved in the future if economies of scale in energy production and/or CO_2 capture and storage can be realized. If, for instance, a CO_2 pipeline network is established in a country or region, then small CO_2 emission sources (including those from biomass energy plants) could be added to any nearby CO_2 pipelines if it is economically viable to do so. A second possibility is that existing large fossil fuel plants with CO_2 capture and storage represent an opportunity for the co-processing of biomass. Co-processing biomass at coal power plants already takes place in a number of countries. However, it must be noted that if biomass is co-processed with a fossil fuel, these plants do not represent new large-scale emissions sources. A third possibility is to build larger biomass energy production plants than the plants typically in place at present. Larger biomass energy production plants have been built or are being planned in a number of countries, typically those with extensive biomass resources. For example, Sweden already has seven combined heat and power plants using biomass at pulp mills, with each plant producing around 130 MW_e equivalent. The size of biomass energy production plants depends on local circumstances, in particular the availability of concentrated biomass sources; pulp mills and sugar processing plants offer concentrated sources of this kind.

Larger plants could also be favoured if there were a shift from the utilization of biomass residues to dedicated energy crops. Several studies have assessed the likely size of future biomass energy production plants, but these studies conflict when it comes to the scale issue. One study, cited in Audus and Freund (2004), surveyed 28 favoured sites using woody biomass crops in Spain and concluded that the average appropriate scale would be in the range 30 to 70 MW_e. This figure is based on the fact that transport distances longer than the assumed maximum of 40 km would render larger plants uneconomic. In contrast, another study based on dedicated energy crops in Brazil and the United States estimated that economies of scale outweigh the extra costs of transporting biomass over long distances. This study found that plant capacities of hundreds of MW_e were feasible (Marrison and Larson, 1995). Other studies have come up with similar findings (Dornburg and Faaij, 2001; Hamelinck and Faaij, 2002). A recent study analyzed a variety of options including both electricity and synthetic fuel production and indicated that large plants processing about 1000 MW_{th} of biomass would tend to be preferred for dedicated energy crops in the United States (Greene *et al.*, 2004).

The size of future emission sources from bioenergy options depends to a large degree on local circumstances and the extent to which economic forces and/or public policies will encourage the development of dedicated energy crops. The projections of annual global biomass energy use rise from 12–60 EJ by 2020, to 70–190 EJ per year by 2050, and to 120–380 EJ by 2100 in the SRES Marker Scenarios (IPCC, 2000), showing that many global energy modellers expect that dedicated energy crops may well become more and more important during the course of this century. So if bioenergy systems prove to be viable at scales suitable for CO_2 capture and storage, then the negative emissions potential of biomass (see Chapter 8) might, during the course of this century, become globally important. However, it is currently unclear to what extent it will be feasible to exploit this potential, both because of the uncertainties about the scale of bioenergy conversion and the extent to which dedicated biomass energy crops will play a role in the energy economy of the future.

In summary, based on the available literature, it is not possible at this stage to make reliable quantitative statements on number of biomass energy production plants that will be built in the future or the likely size of their CO_2 emissions.

2.6 Gaps in knowledge

Whilst it is possible to determine emission source data for the year 2000 (CO_2 concentration and point source geographical location) with a reasonable degree of accuracy for most industrial sectors, it is more difficult to predict the future location of emission point sources. Whilst all projections indicate there will be an increase in CO_2 emissions, determining the actual locations for new plants currently remains a subjective business.

A detailed description of the storage capacity for the world's sedimentary basins is required. Although capacity estimates have been made, they do not yet constitute a full resource assessment. Such information is essential to establish a better picture of the existing opportunities for storing the CO_2 generated at large point sources. At present, only a simplistic assessment is possible based on the limited data about the storage capacity currently available in sedimentary basins.

An analysis of the storage potential in the ocean for emissions from large point sources was not possible because detailed mapping indicating the relationship between storage locations in the oceans and point source emissions has not yet been carefully assessed.

This chapter highlights the fact that fossil fuel-based hydrogen production from large centralized plants will potentially result in the generation of more high-concentration emission sources. However, it is not currently possible to predict with any accuracy the number of these point sources in the future, or when they will be established, because of market development uncertainties surrounding hydrogen as an energy carrier. For example, before high-concentration CO_2 sources associated with hydrogen production for energy can be exploited, cost-effective end-use technologies for hydrogen (e.g., low-temperature fuel cells) must be readily available on the market. In addition, it is expected that it will take decades to build a hydrogen infrastructure that will bring the hydrogen from large centralized sources (where CCS is practical) to consumers.

Synthetic liquid fuels production or the co-production of liquid fuels and electricity via the gasification of coal or other solid feedstocks or petroleum residuals can also lead to the generation of concentrated streams of CO_2. It is unclear at the present time to what extent such synthetic fuels will be produced as alternatives to crude-oil-derived hydrocarbon fuels. The co-production options, which seem especially promising, require market reforms that make it possible to co-produce electricity at a competitive market price.

During the course of this century, biomass energy systems might become significant new large CO_2 sources, but this depends on the extent to which bioenergy conversion will take place in large plants, and the global significance of this option may well depend critically on the extent to which dedicated energy crops are pursued.

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