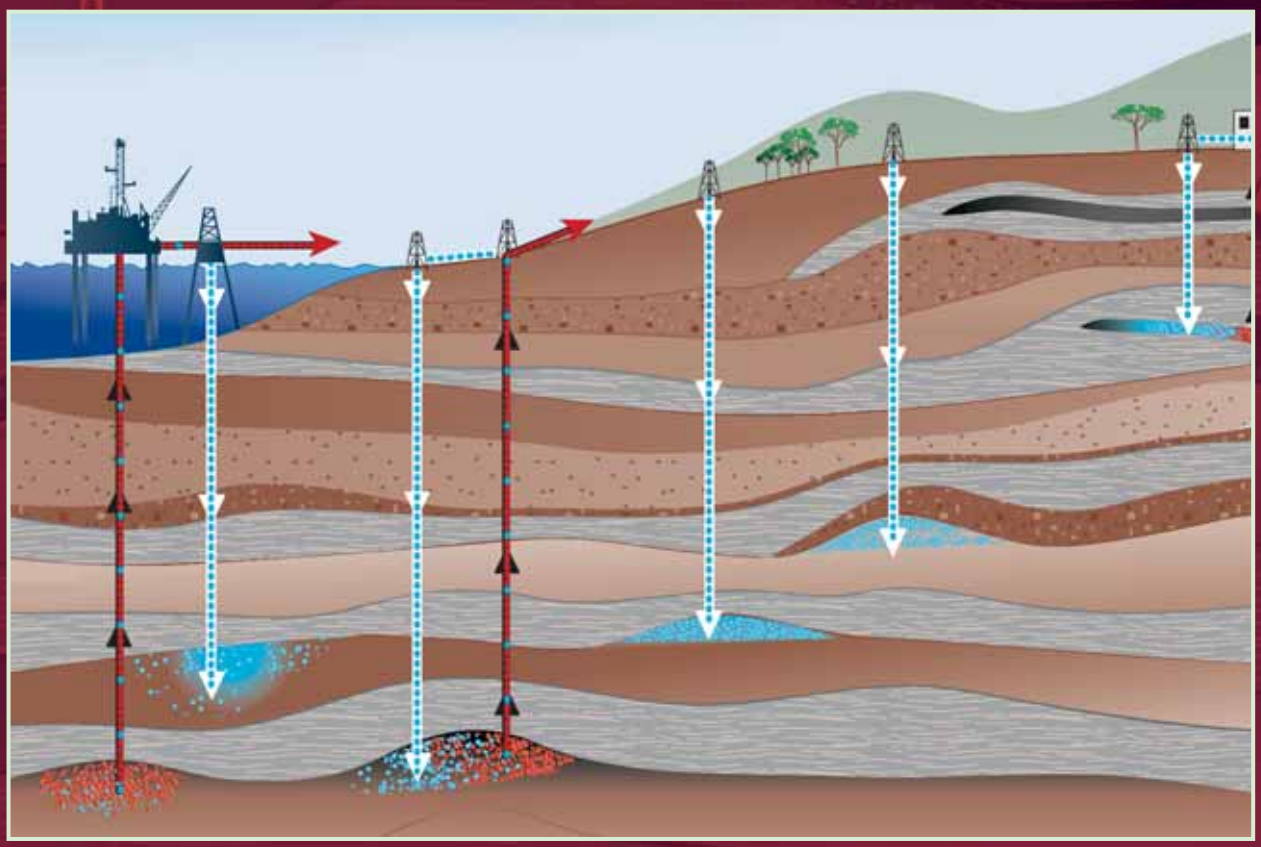
CARBON DIOXIDE CAPTURE AND STORAGE

Summary for Policymakers and Technical Summary



WMO

Intergovernmental Panel on Climate Change

UNEP

IPCC Special Report

Carbon Dioxide Capture and Storage

Summary for Policymakers

A report of Working Group III of the IPCC

and

Technical Summary

A report accepted by Working Group III of the IPCC
but not approved in detail

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of the United Nations Framework Convention on Climate Change

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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.

Michel Jarraud
Secretary-General,
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Executive Director,
United Nations Environment Programme and
Director-General,
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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.

[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 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,

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

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.

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

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IPCC Special Report

Carbon Dioxide Capture and Storage

Summary for Policymakers

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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

[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).

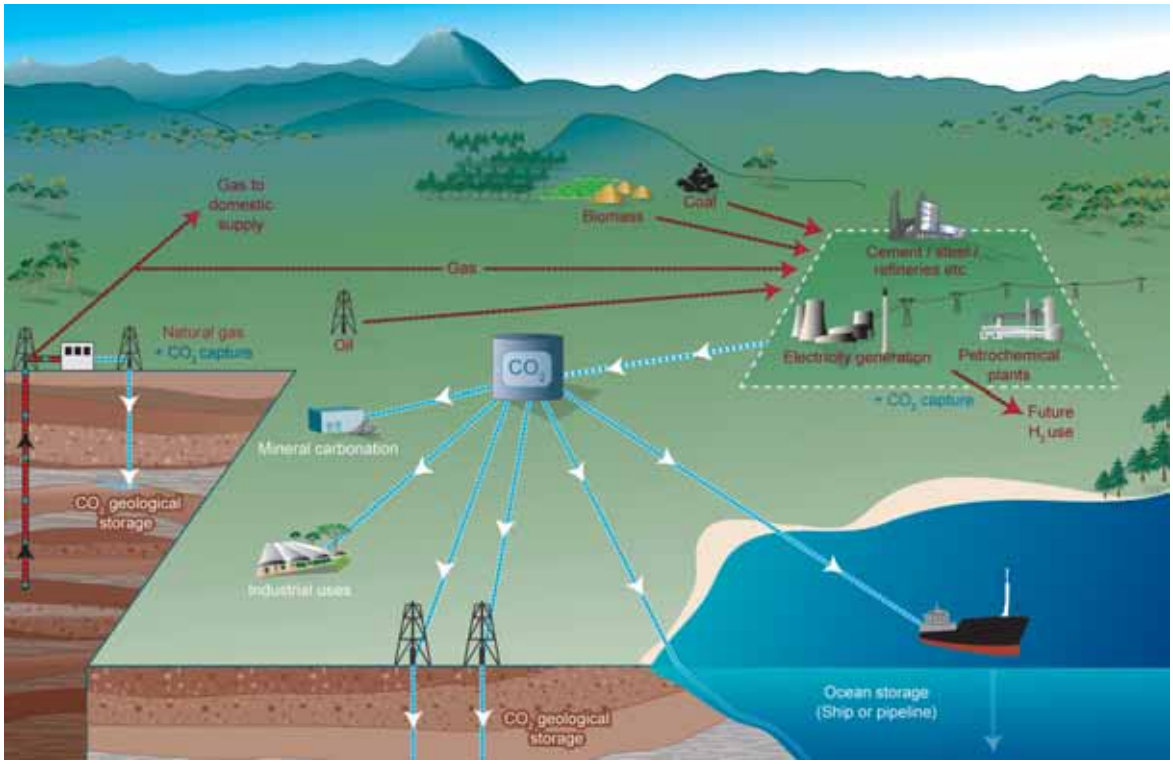

Figure SPM.1. Schematic diagram of possible CCS systems showing the sources for which CCS might be relevant, transport of CO_2 and storage options (Courtesy of CO2CRC).

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–

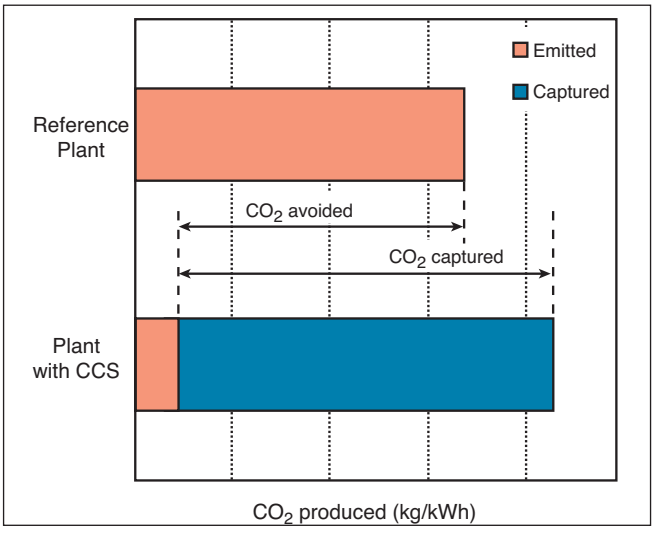

Figure SPM.2. CO_2 capture and storage from power plants. The increased CO_2 production resulting from the loss in overall efficiency of power plants due to the additional energy required for capture, transport and storage and any leakage from transport result in a larger amount of "CO_2 produced per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

[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-

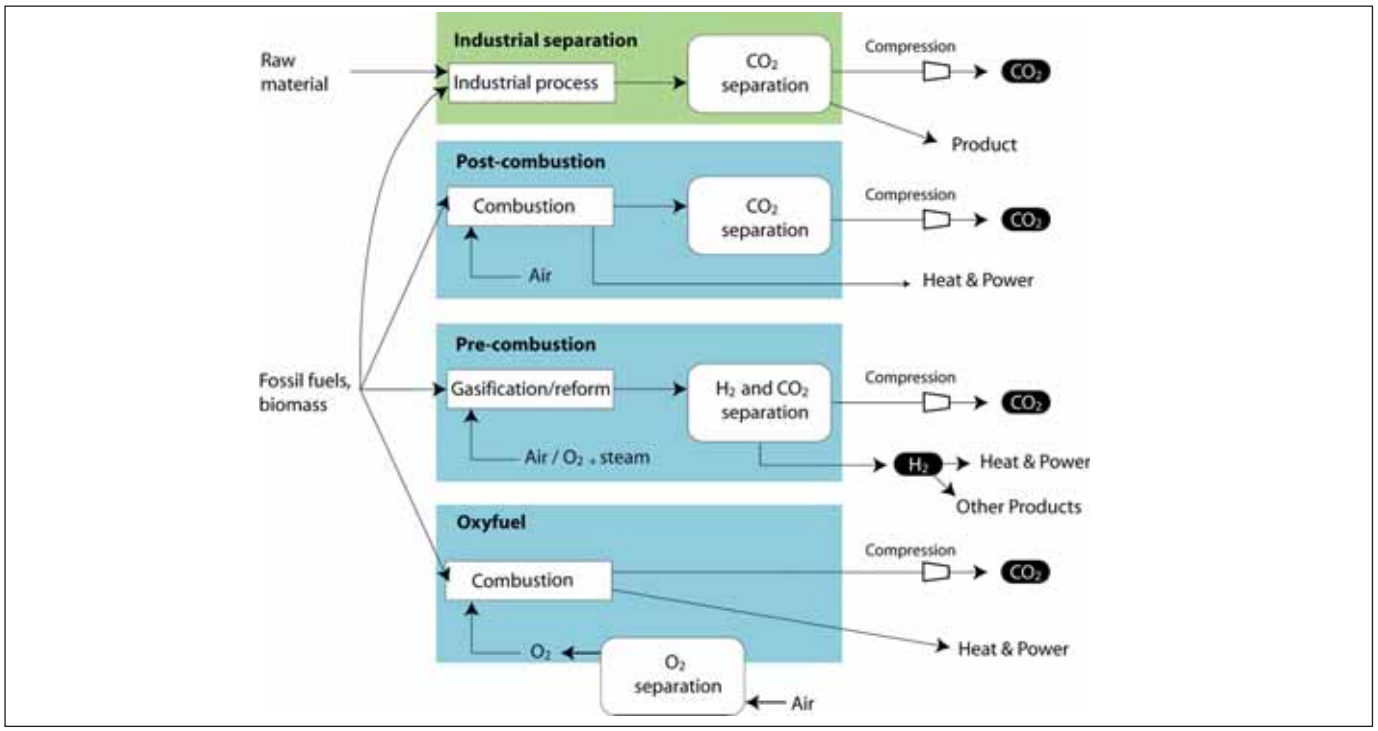

Figure SPM.3. Schematic representation of capture systems. Fuels and products are indicated for oxyfuel combustion, pre-combustion (including hydrogen and fertilizer production), post-combustion and industrial sources of CO_2 (including natural gas processing facilities and steel and cement production)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

[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.

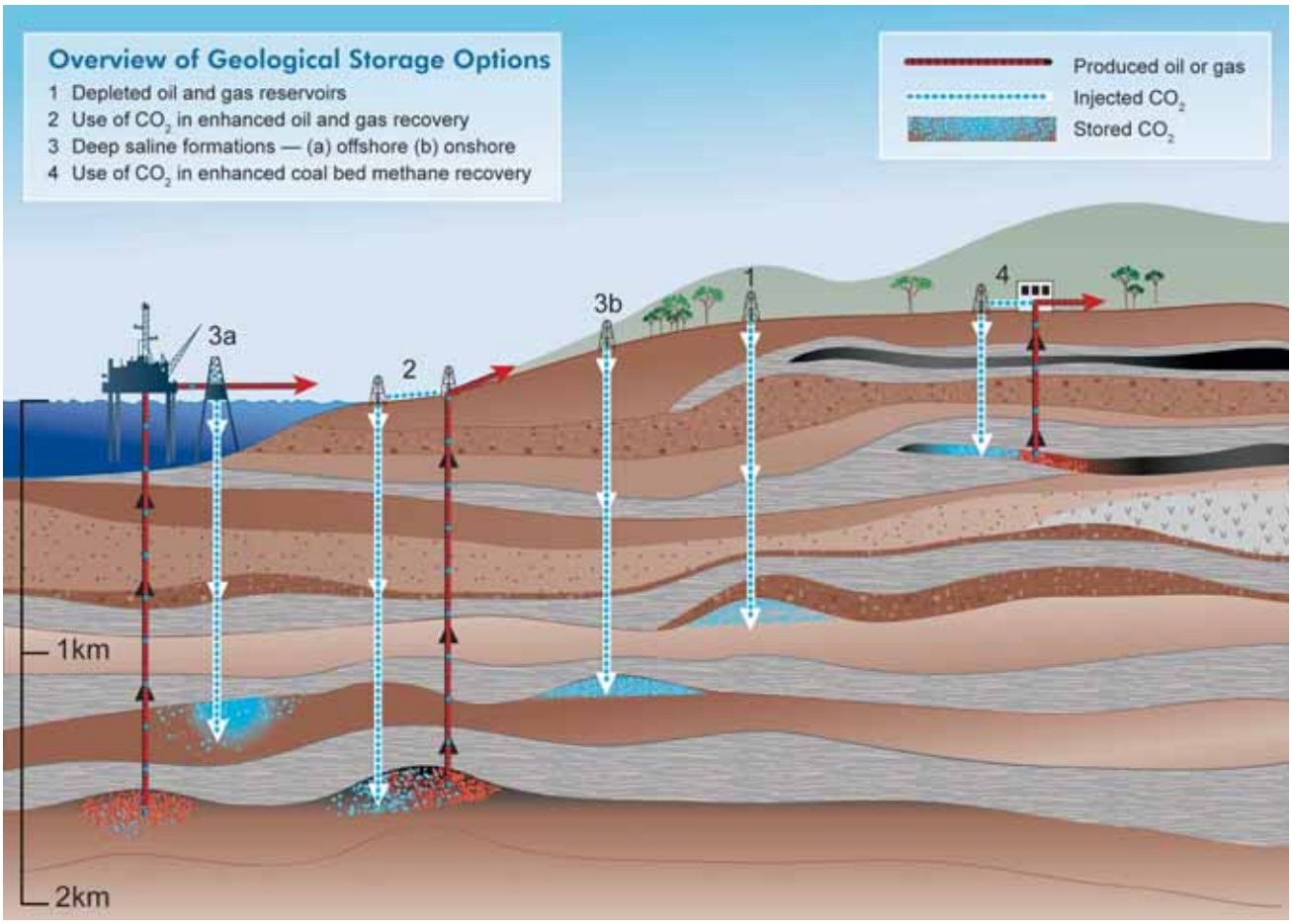

Figure SPM.4. Overview of geological storage options (based on Figure 5.3) (Courtesy CO2CRC).

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

[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.

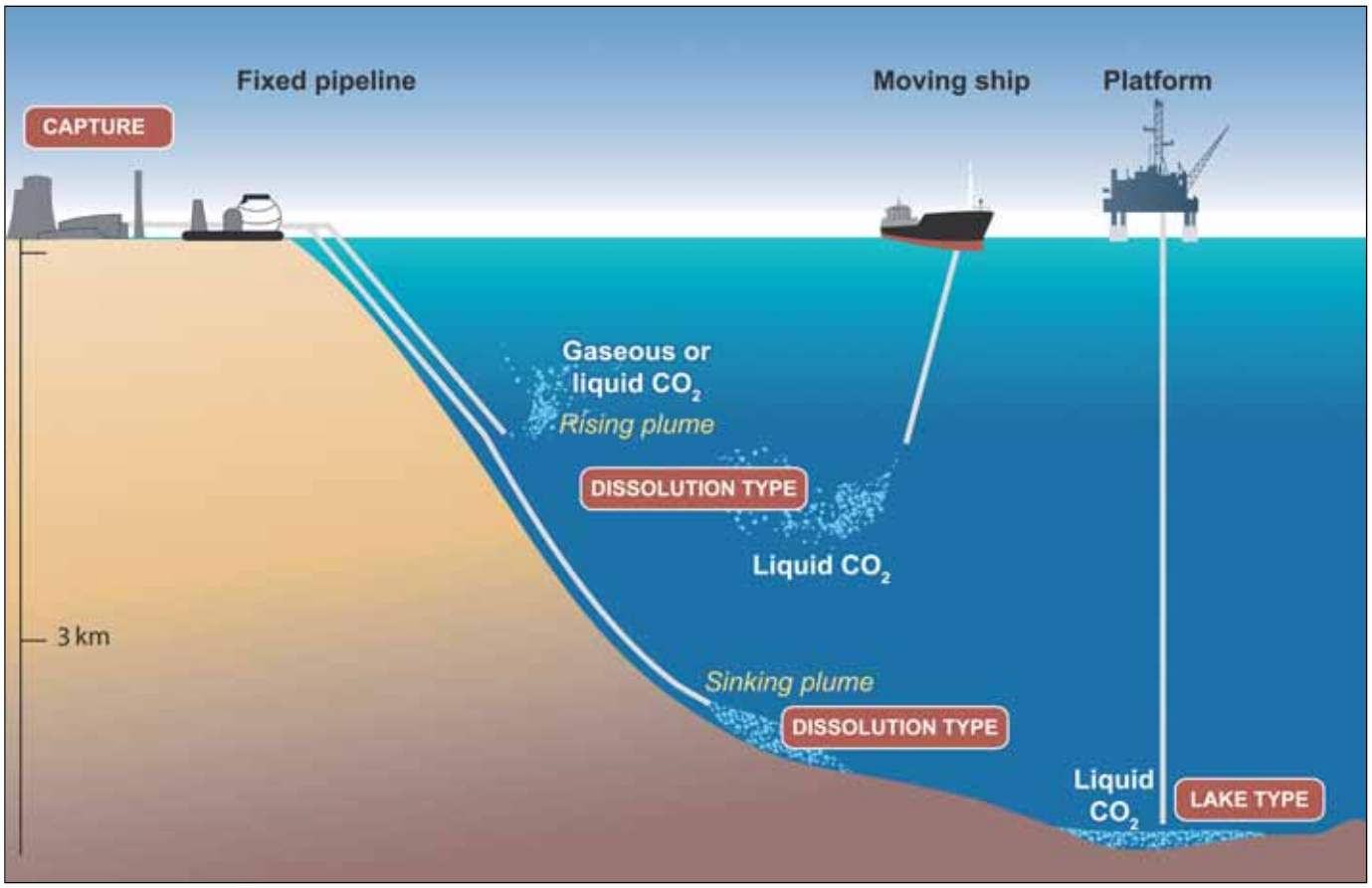

Figure SPM.5. Overview of ocean storage concepts. In "dissolution type" ocean storage, the CO_2 rapidly dissolves in the ocean water, whereas in "lake type" ocean storage, the CO_2 is initially a liquid on the sea floor (Courtesy CO2CRC).

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).

[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'

[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)

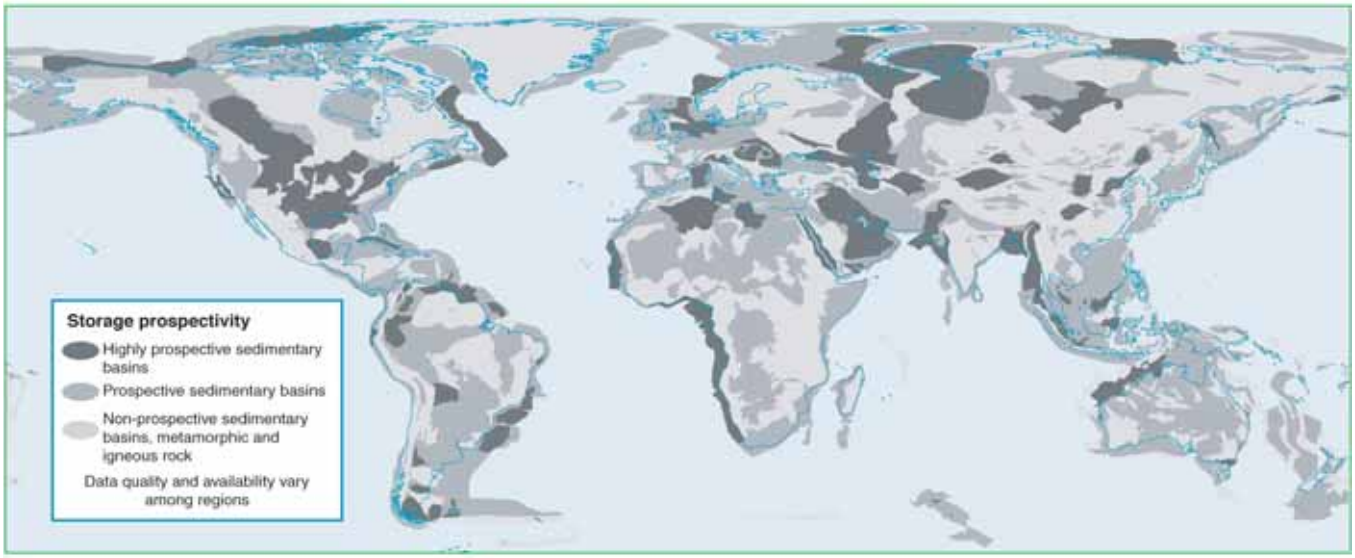

Figure SPM.6b. Prospective areas in sedimentary basins where suitable saline formations, oil or gas fields or coal beds may be found. Locations for storage in coal beds are only partly included. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present in 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

[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

[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.

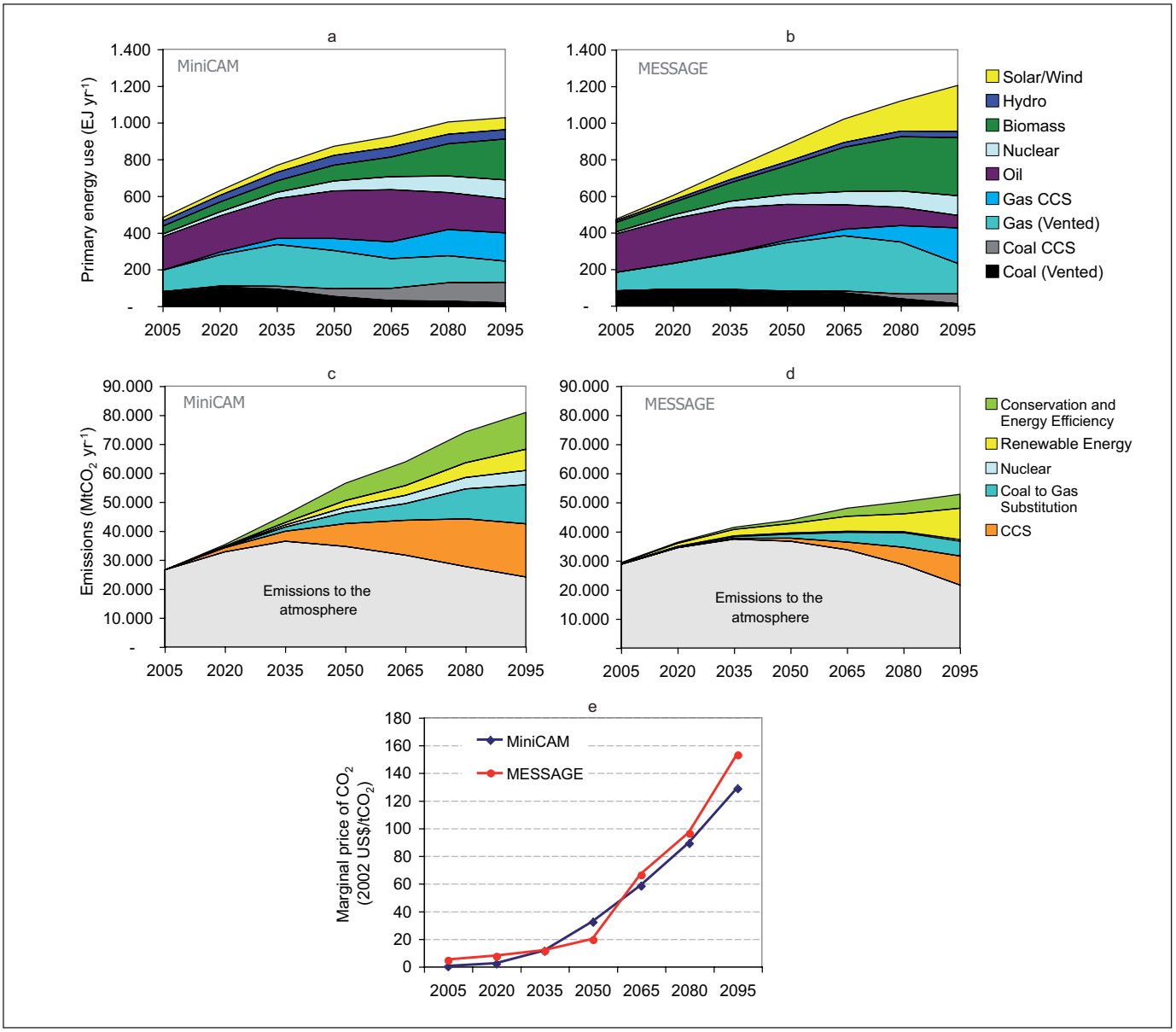

Figure SPM.7. These figures are an illustrative example of the global potential contribution of CCS as part of a mitigation portfolio. They are based on two alternative integrated assessment models (MESSAGE and MiniCAM) while adopt the same assumptions for the main emissions drivers. The results would 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 (*p*H decrease >0.4) over approximately 1% of the ocean volume. For comparison purposes: in such a stabilization case without ocean storage, a *p*H decrease >0.25 relative to pre-industrial levels at the entire ocean surface can be expected. A 0.2 to 0.4 *p*H 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 *p*H 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

[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).*

[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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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.

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

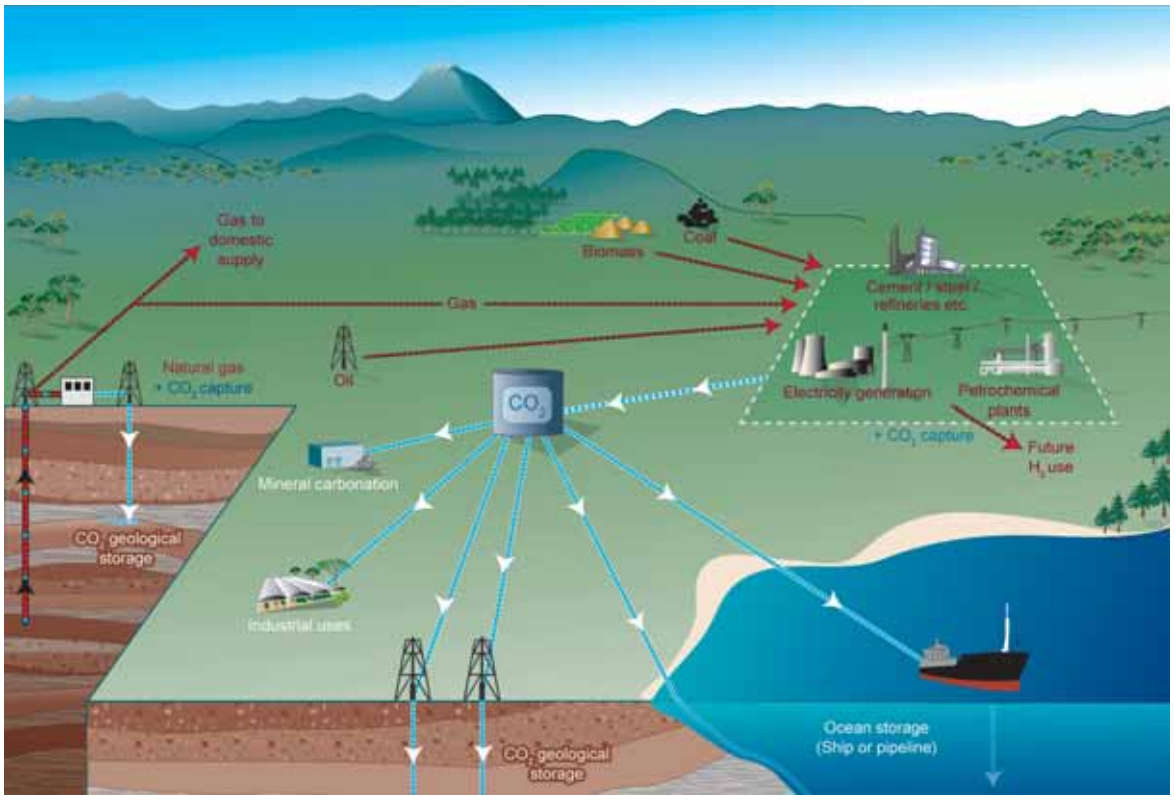

Figure TS.1. Schematic diagram of possible CCS systems. It shows the sources for which CCS might be relevant, as well as CO_2 transport and storage options (Courtesy CO2CRC).

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".

[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

[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)

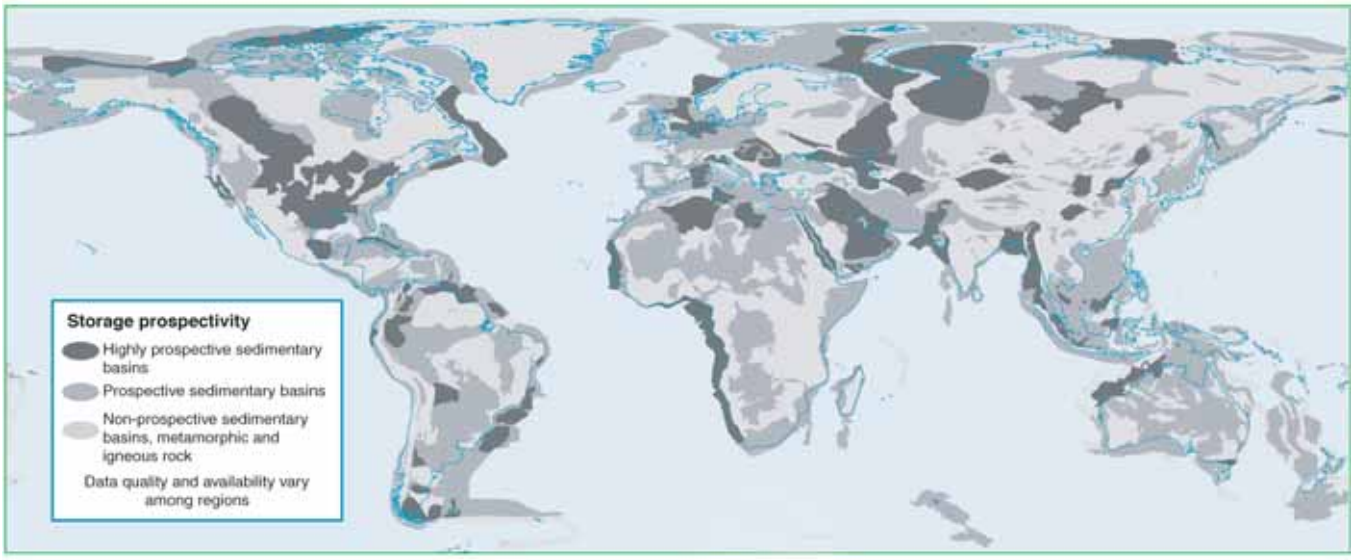

Figure TS.2b. Prospective areas in sedimentary basins where suitable saline formations, oil or gas fields, or coal beds may be found. Locations for storage in coal beds are only partly included. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present in 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.

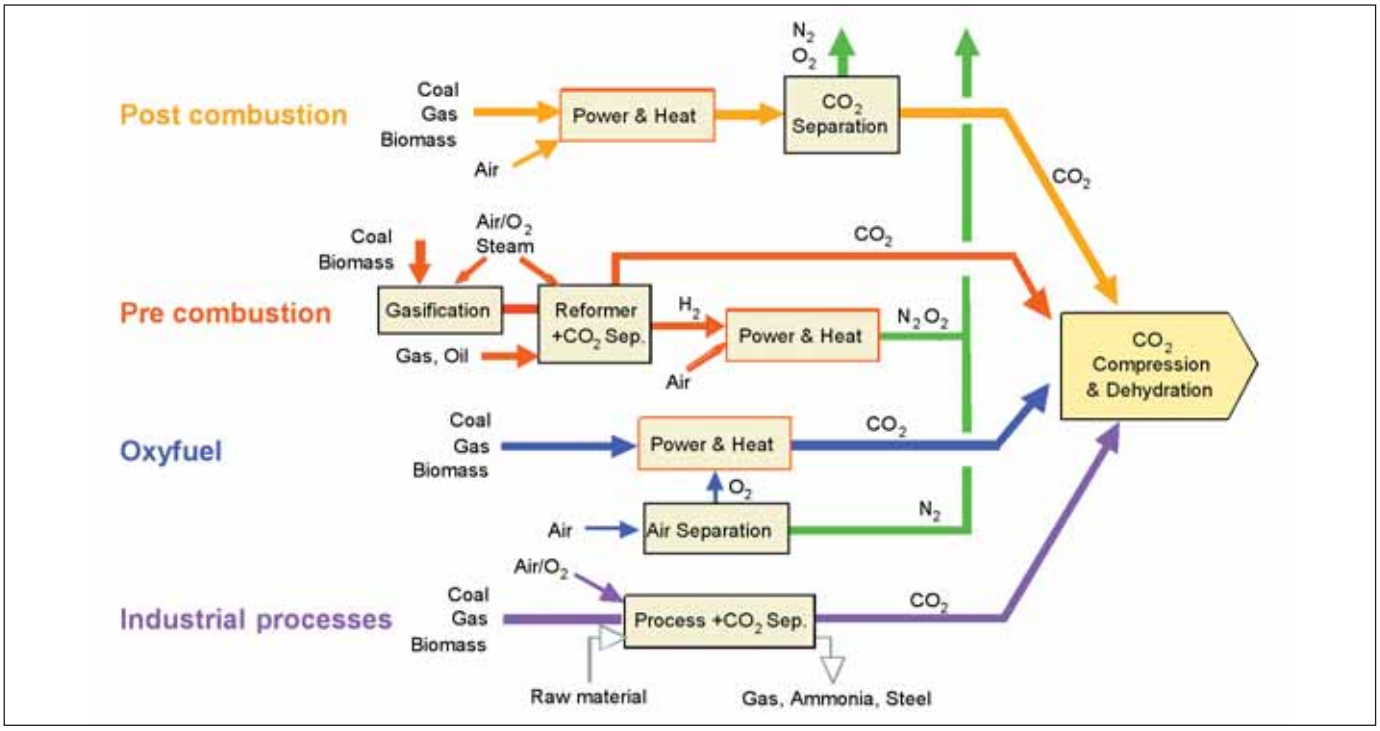

Figure TS.3. Overview of CO_2 capture processes and systems.

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.

[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$/kWh)	0.012	0.024	0.017	0.018	0.034	0.027	0.009	0.022	0.016
Percent increase in COE with capture (%)	37	69	46	42	66	57	20	55	33
Cost of net CO_2 captured (US$/$tCO_2$)	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 MW biomass IGCC plant is estimated to be about 80 US$/$tCO_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$/$tCO_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.

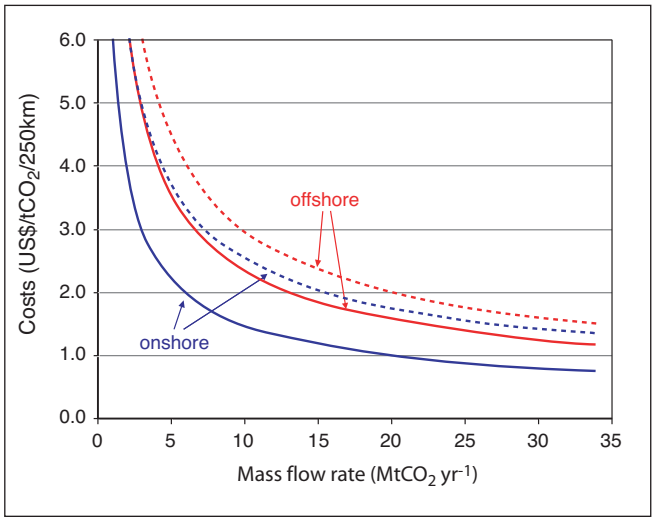

Figure TS.5. Transport costs for onshore pipelines and offshore pipelines, in US$ per tCO$_2$ per 250 km as a function of the CO_2 mass flow rate. The graph shows high estimates (dotted lines) and low estimates (solid lines).

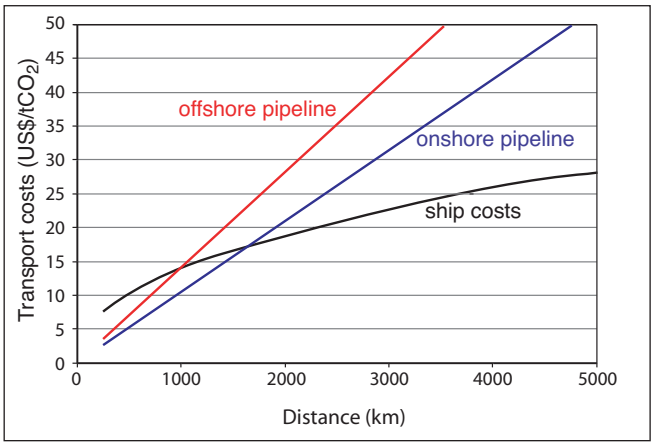

Figure TS.6. Costs, plotted as US$/tCO$_2$ transported against distance, for onshore pipelines, offshore pipelines and ship transport. Pipeline costs are given for a mass flow of 6 MtCO$_2$ yr^{-1}. Ship costs include intermediate storage facilities, harbour fees, fuel costs, and loading and unloading 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_2S) 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.

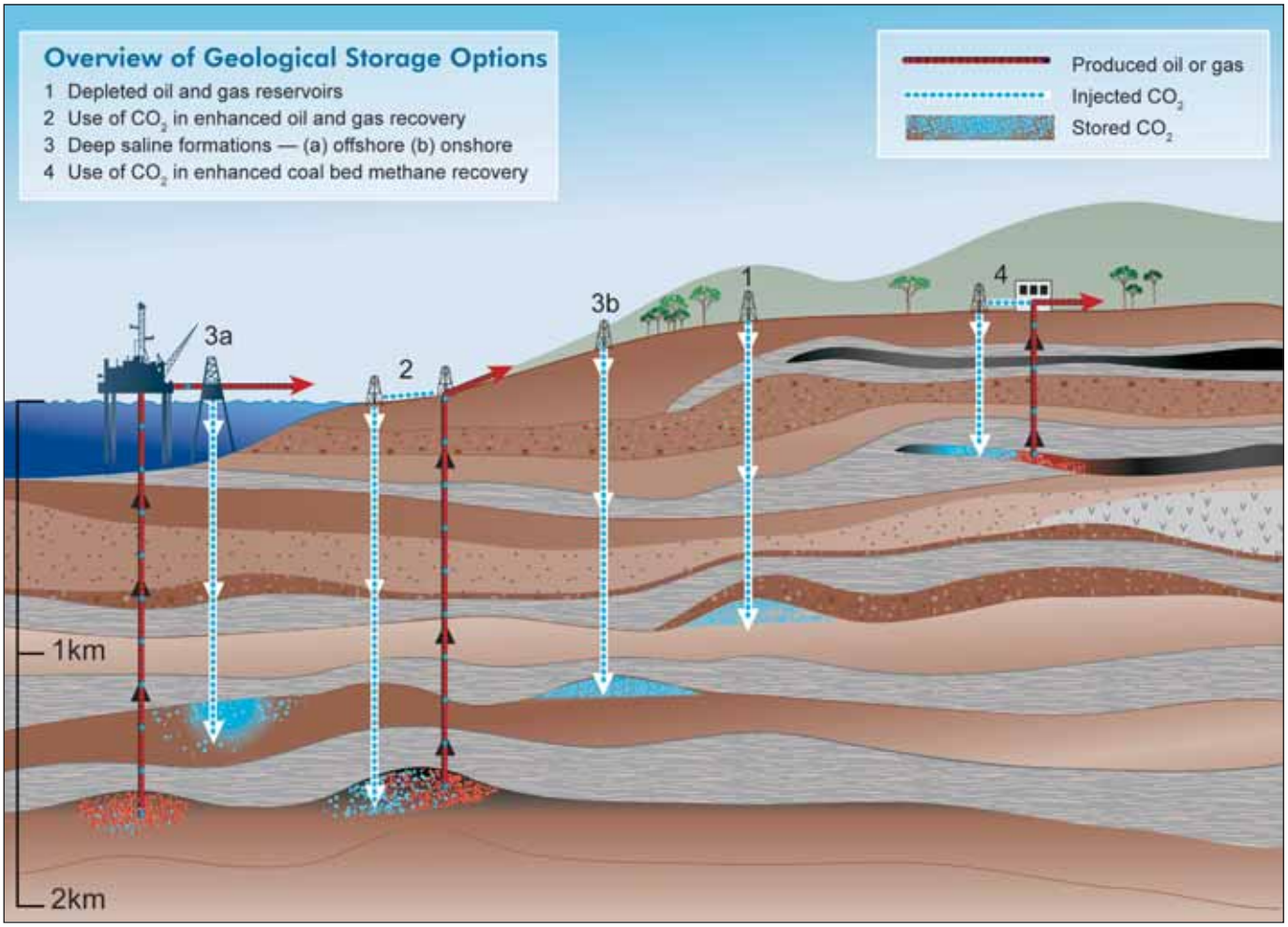

Figure TS.7. Methods for storing CO_2 in deep underground geological formations. Two methods may be combined with the recovery of hydrocarbons: EOR (2) and ECBM (4). See text for explanation of these methods (Courtesy CO2CRC).

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 $GtCO_2$.

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 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,

[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.

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). Techniques to remove CO_2 from soils and groundwater are also available, but they are likely to be costly. Experience

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

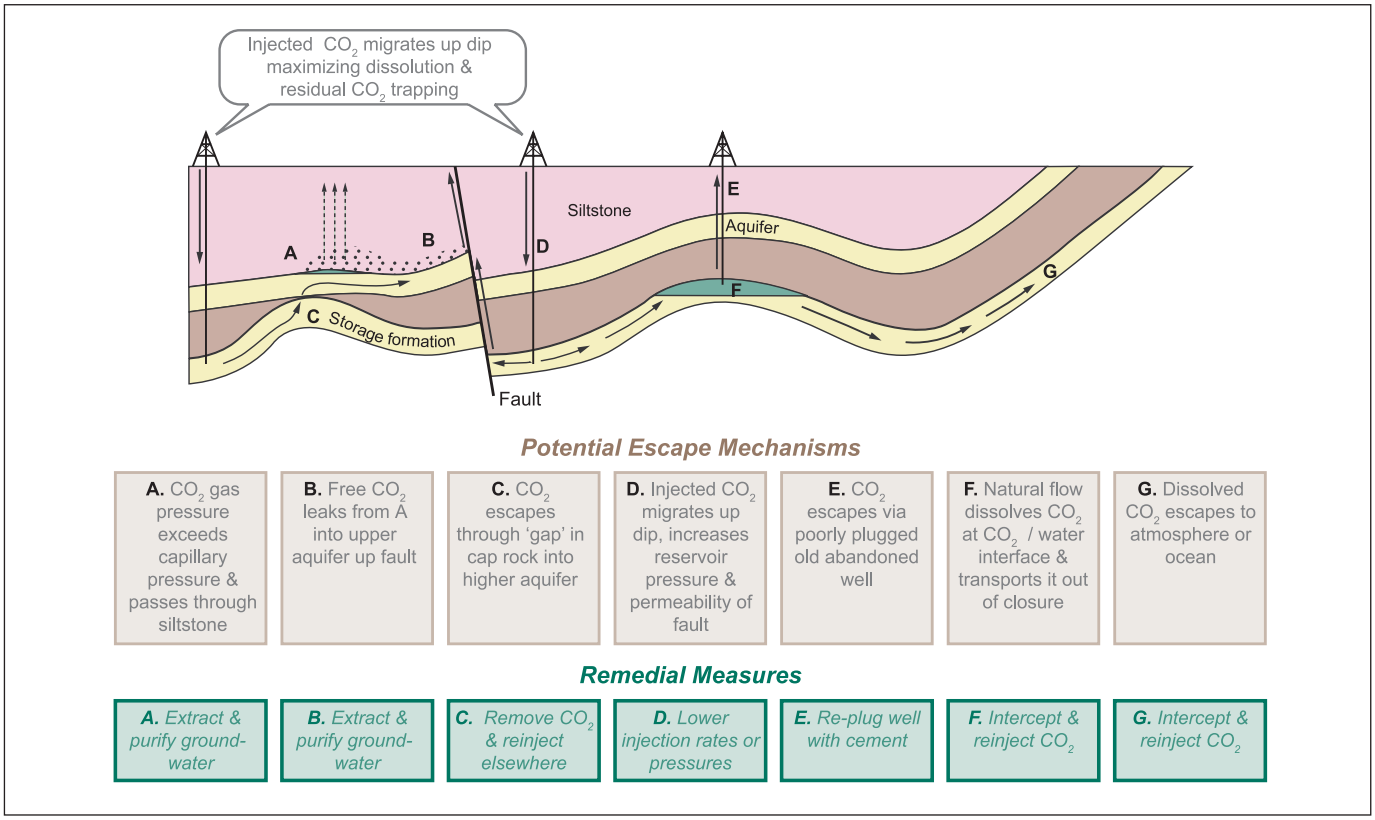

Figure TS.8. Potential leakage routes and remediation techniques for CO_2 injected into saline formations. The remediation technique would depend on the potential leakage routes identified in a reservoir (Courtesy CO2CRC).

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 depends strongly on oil and gas prices. In this regard, the literature basis for this report does not take into account the

[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.

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.

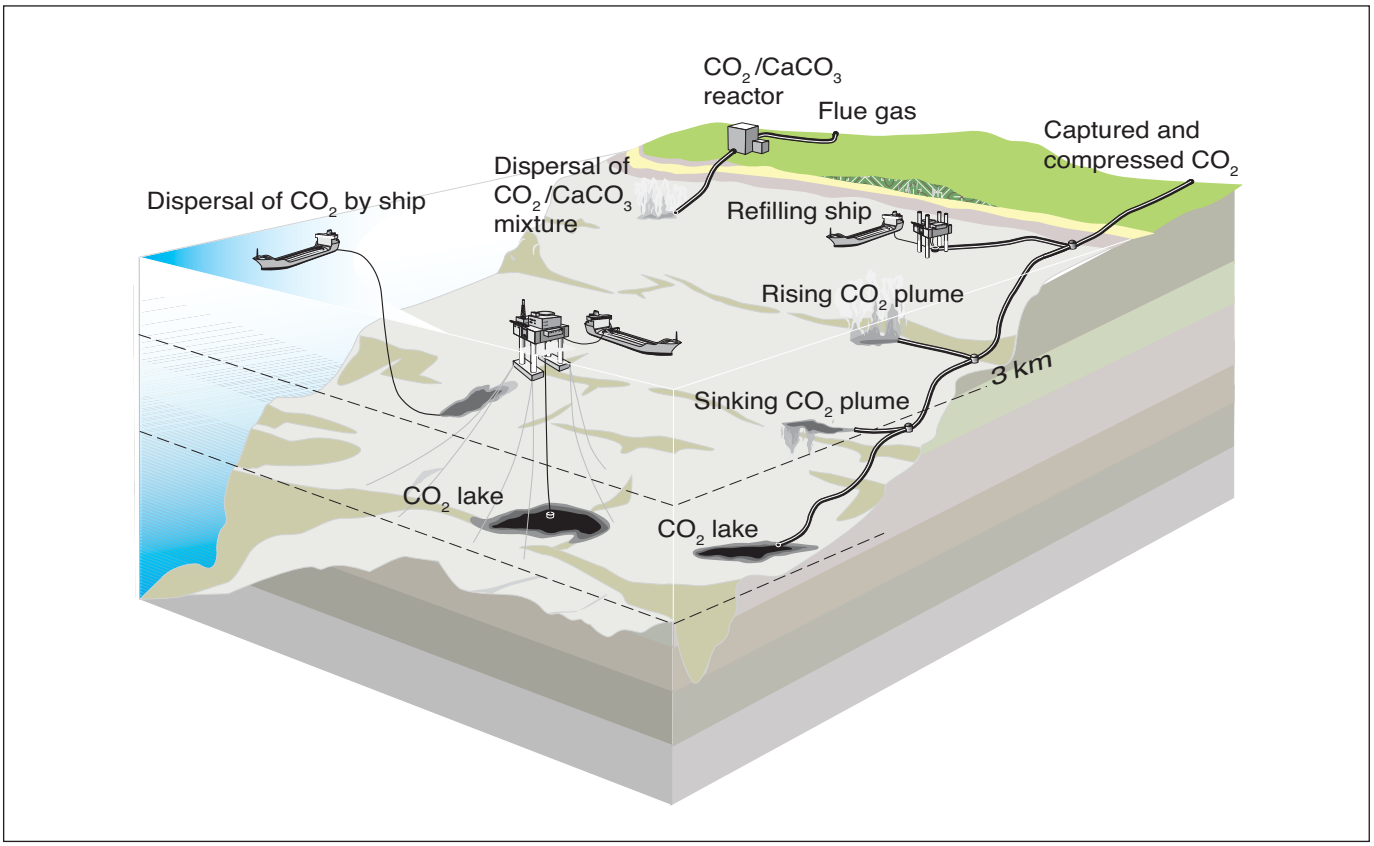

Figure TS.9. Methods of ocean storage.

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

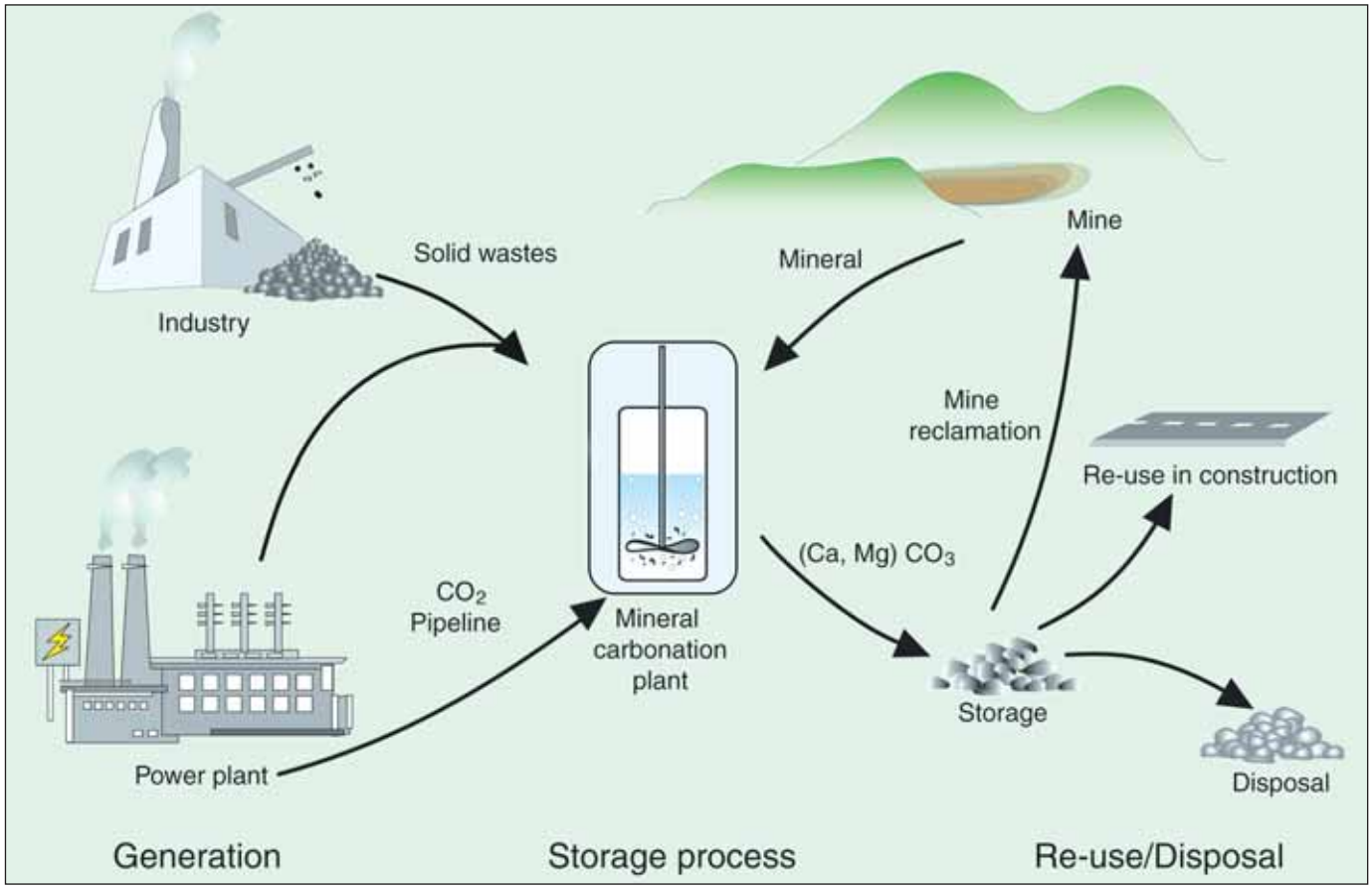

Figure TS.10. Material fluxes and process steps associated with the mineral carbonation of silicate rocks or industrial residues (Courtesy ECN).

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'.

[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

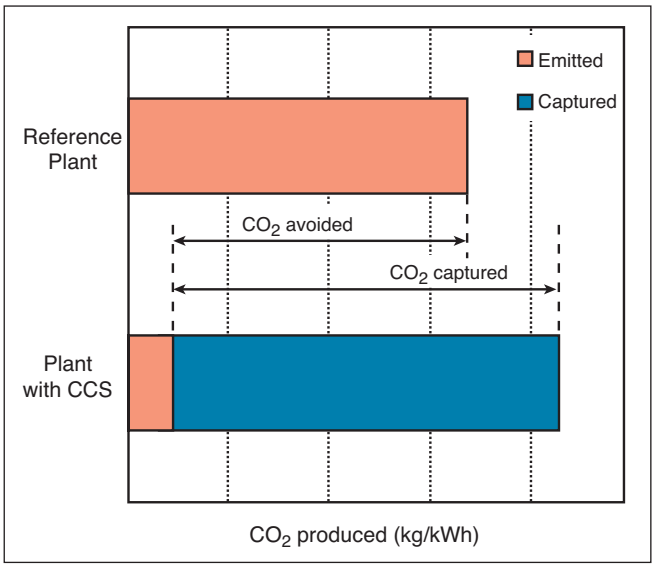

Figure TS.11. CO_2 capture and storage from power plants. The increased CO_2 production resulting from loss in overall efficiency of power plants due to the additional energy required for capture, transport and storage, and any leakage from transport result in a larger amount of "CO_2 produced per unit 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$/t$CO_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$/t$CO_2$ avoided (US$/tC avoided)	PC reference plant US$/t$CO_2$ 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)

[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.

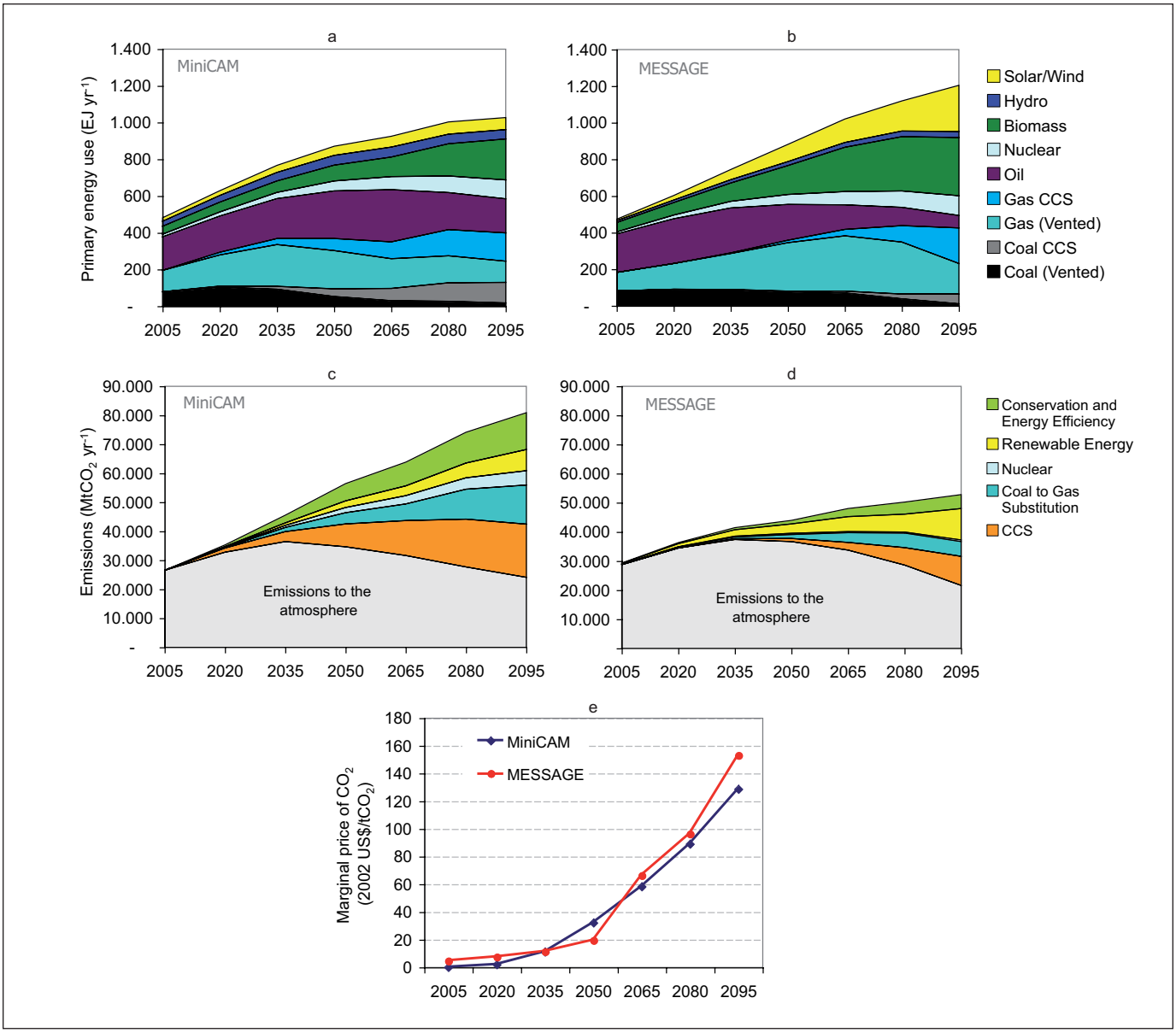

Figure TS.12. These figures are an illustrative example of the global potential contribution of CCS as part of a mitigation portfolio. They are based on two alternative integrated assessment models (MESSAGE and MiniCAM) adopting the same assumptions for the main emissions drivers. The results would vary 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

[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.

Annex I: Glossary, acronyms and abbreviations

The definitions in this glossary refer to the use of the terms in the context of the Summary for Policymakers of the Special Report on Carbon dioxide Capture and Storage.

Abatement
Reduction in the degree or intensity of emissions or other pollutants.

Absorption
Chemical or physical take-up of molecules into the bulk of a solid or liquid, forming either a solution or compound.

Acid gas
Any gas mixture that turns to an acid when dissolved in water (normally refers to H_2S + CO_2 from sour gas (q.v.)).

Adsorption
The uptake of molecules on the surface of a solid or a liquid.

Amine
Organic chemical compound containing one or more nitrogens in -NH_2, -NH or -N groups.

Anthropogenic source
Source which is man-made as opposed to natural.

Aquifer
Geological structure containing water and with significant permeability to allow flow; it is bound by seals.

Basalt
A type of basic igneous rock which is typically erupted from a volcano.

Baseline
The datum against which change is measured.

Biomass
Matter derived recently from the biosphere.

Biomass-based CCS
Carbon capture and storage in which the feedstock (q.v.) is biomass

Bituminous coal
An intermediate rank of coal falling between the extremes of peat and anthracite, and closer to anthracite.

Blow-out
Refers to catastrophic failure of a well when the petroleum fluids or water flow unrestricted to the surface.

Bottom-up model
A model that includes technological and engineering details in the analysis.

Boundary
In GHG accounting, the separation between accounting units, be they national, organizational, operational, business units or sectors.

Buoyancy
Tendency of a fluid or solid to rise through a fluid of higher density.

Cap rock
Rock of very low permeability that acts as an upper seal to prevent fluid flow out of a reservoir.

Capture efficiency
The fraction of CO_2 separated from the gas stream of a source

Carbon credit
A convertible and transferable instrument that allows an organization to benefit financially from an emission reduction.

Carbonate
Natural minerals composed of various anions bonded to a CO_3^{2-} cation (e.g. calcite, dolomite, siderite, limestone).

Carbonate neutralization
A method for storing carbon in the ocean based upon the reaction of CO_2 with a mineral carbonate such as limestone to produce bicarbonate anions and soluble cations.

CCS
Carbon dioxide capture and storage

CDM
Clean development mechanism: a Kyoto Protocol mechanism to assist non-Annex I countries to contribute to the objectives of the Protocol and help Annex I countries to meet their commitments.

CO_2 avoided
The difference between CO_2 captured, transmitted and/or stored, and the amount of CO_2 generated by a system without capture, net of the emissions not captured by a system with CO_2 capture.

Co-firing
The simultaneous use of more than one fuel in a power plant or industrial process.

Cryogenic
Pertaining to low temperatures, usually under about -100°C.

Deep saline formation
A deep underground rock formation composed of permeable materials and containing highly saline fluids.

Deep sea
The sea below 1000m depth.

Demonstration phase
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.

Dense phase
A gas compressed to a density approaching that of the liquid.

Depleted
Of a reservoir: one where production is significantly reduced.

ECBM
Enhanced coal bed methane recovery; 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.

Economic potential
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).

Economically feasible under specific conditions
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.

EGR
Enhanced gas recovery: the recovery of gas additional to that produced naturally by fluid injection or other means..

Emission factor
A normalized measure of GHG emissions in terms of activity, e.g., tonnes of GHG emitted per tonne of fuel consumed.

Emissions trading
A trading scheme that allows permits for the release of a specified number of tonnes of a pollutant to be sold and bought.

Enhanced gas recovery
See EGR.

Enhanced oil recovery
See EOR

EOR
Enhanced oil recovery: the recovery of oil additional to that produced naturally by fluid injection or other means.

Fault
In geology, a surface at which strata are no longer continuous, but displaced.

Feedstock
The material that is fed to a process

Fixation
The immobilization of CO_2 by its reaction with another material to produce a stable compound

Flue gas
Gases produced by combustion of a fuel that are normally emitted to the atmosphere.

Formation
A body of rock of considerable extent with distinctive characteristics that allow geologists to map, describe, and name it.

Formation water
Water that occurs naturally within the pores of rock formations.

Fracture
Any break in rock along which no significant movement has occurred.

Fuel cell
Electrochemical device in which a fuel is oxidized in a controlled manner to produce an electric current and heat directly.

Fugitive emission
Any releases of gases or vapours from anthropogenic activities such as the processing or transportation of gas or petroleum.

Gas turbine
A machine in which a fuel is burned with compressed air or oxygen and mechanical work is recovered by the expansion of the hot products.

Gasification
Process by which a carbon-containing solid fuel is transformed into a carbon- and hydrogen-containing gaseous fuel by reaction with air or oxygen and steam.

Geochemical trapping
The retention of injected CO_2 by geochemical reactions.

Hydrate
An ice-like compound formed by the reaction of water and CO_2, CH_4 or similar gases.

IGCC
Integrated gasification combined cycle: power generation in which hydrocarbons or coal are gasified (q.v.) and the gas is used as a fuel to drive both a gas and a steam turbine.

Injection
The process of using pressure to force fluids down wells.

Injection well
A well in which fluids are injected rather than produced.

JI
Joint Implementation: under the Kyoto Protocol, it allows a Party with a GHG emission target to receive credits from other Annex 1 Parties.

Kyoto Protocol
Protocol to the United Nations Framework Convention on Climate Change, which was adopted at Kyoto on 11 December 1997.

Leakage
In respect of carbon trading, the change of anthropogenic emissions by sources or removals by sinks which occurs outside the project boundary.

Leakage
In respect of carbon storage, the escape of injected fluid from storage.

LHV
Lower heating value: energy released from the combustion of a fuel that excludes the latent heat of water.

Limestone
A sedimentary rock made mostly of the mineral calcite (calcium carbonate), usually formed from shells of dead organisms.

London Convention
On the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, which was adopted at London, Mexico City, Moscow and Washington on 29 December 1972.

London Protocol
Protocol to the Convention adopted in London on 2 November 1996 but which had not entered into force at the time of writing.

Low-carbon energy carrier
Fuel that provides low fuel-cycle-wide emissions of CO_2, such as methanol.

MEA
Mono-ethanolamine

Membrane
A sheet or block of material that selectively separates the components of a fluid mixture.

Migration
The movement of fluids in reservoir rocks.

Mitigation
The process of reducing the impact of any failure.

Monitoring
The process of measuring the quantity of carbon dioxide stored and its location.

MWh
Megawatt hour

National Greenhouse Gas Inventory
An inventory of anthropogenic emissions by sources and removals by sinks of greenhouse gases prepared by Parties to the UNFCCC.

Natural analogue
A natural occurrence that mirrors in most essential elements an intended or actual human activity.

NGCC
Natural gas combined cycle: natural-gas-fired power plant with gas and steam turbines.

OSPAR
Convention for the Protection of the Marine Environment of the North-East Atlantic, which was adopted at Paris on 22 September 1992.

Oxyfuel combustion
Combustion of a fuel with pure oxygen or a mixture of oxygen, water and carbon dioxide.

Partial pressure
The pressure that would be exerted by a particular gas in a mixture of gases if the other gases were not present.

PC
Pulverized coal: usually used in connection with boilers fed with finely ground coal.

Permeability
Ability to flow or transmit fluids through a porous solid such as rock.

Point source
An emission source that is confined to a single small location

Pore space
Space between rock or sediment grains that can contain fluids.

Post-combustion capture
The capture of carbon dioxide after combustion.

Pre-combustion capture
The capture of carbon dioxide following the processing of the fuel before combustion.

Prospectivity
A qualitative assessment of the likelihood that a suitable storage location is present in a given area based on the available information

Reduction commitment
A commitment by a Party to the Kyoto Protocol to meet its quantified emission limit.

Remediation
The process of correcting any source of failure.

Renewables
Energy sources that are inherently renewable such as solar energy, hydropower, wind, and biomass.

Representative value
The representative value is based on the average of the values in the different studies.

Reservoir
A subsurface body of rock with sufficient porosity and permeability to store and transmit fluids.

Retrofit
A modification of the existing equipment to upgrade and incorporate changes after installation.

Risk assessment
Part of a risk-management system.

Saline formation
Sedimentary rocks saturated with formation waters containing high concentrations of dissolved salts.

Scenario
A plausible description of the future based on an internally consistent set of assumptions about key relationships and driving forces.

Scrubber
A gas-liquid contacting device for the purification of gases or capture of a gaseous component.

Seabed
Borderline between the free water and the top of the bottom sediment.

Seal
An impermeable rock that forms a barrier above and around a reservoir such that fluids are held in the reservoir.

Sedimentary basin
Natural large-scale depression in the earth's surface that is filled with sediments.

Seismic technique
Measurement of the properties of rocks by the speed of sound waves generated artificially or naturally.

Sink
The natural uptake of CO_2 from the atmosphere, typically in soils, forests or the oceans.

Source
Any process, activity or mechanism that releases a greenhouse gas, an aerosol, or a precursor thereof into the atmosphere.

SRES
Special Report on Emissions Scenarios; used as a basis for the climate projections in the TAR (q.v.).

Stabilization
Relating to the stabilization atmospheric concentrations of greenhouse gases.

Stable geological formation
A formation (q.v.) that has not recently been disturbed by tectonic movement.

Storage
A process for retaining captured CO_2 so that it does not reach the atmosphere.

Supercritical
At a temperature and pressure above the critical temperature and pressure of the substance concerned.

Sustainable
Of development, that which is sustainable in ecological, social and economic areas.

TAR
Third Assessment Report of the Intergovernmental Panel on Climate Change

Technical potential
The amount by which it is possible to reduce greenhouse gas emissions by implementing a technology or practice that has reached the demonstration phase.

Top-down model
A model based on applying macro-economic theory and econometric techniques to historical data about consumption, prices, etc.

Trap
A geological structure that physically retains fluids that are lighter than the background fluids, e.g. an inverted cup.

UNFCCC
United Nations Framework Convention on Climate Change, which was adopted at New York on 9 May 1992.

Unminable
Extremely unlikely to be mined under current or foreseeable economic conditions

Upper ocean
The ocean above 1000m depth.

Verification
The proving, to a standard still to be decided, of the results of monitoring (q.v.). In the context of CDM, the independent review by a designated operational entity of monitored reductions in anthropogenic emissions.

Well
Manmade hole drilled into the earth to produce liquids or gases, or to allow the injection of fluids.

Annex II List of major IPCC reports

Climate Change - The IPCC Scientific Assessment
The 1990 report of the IPCC Scientific Assessment Working Group

Climate Change - The IPCC Impacts Assessment
The 1990 report of the IPCC Impacts Assessment Working Group

Climate Change - The IPCC Response Strategies
The 1990 report of the IPCC Response Strategies Working Group

Emissions Scenarios
Prepared by the IPCC Response Strategies Working Group, 1990

Assessment of the Vulnerability of Coastal Areas to Sea Level Rise - A Common Methodology, 1991

Climate Change 1992 - The Supplementary Report to the IPCC Scientific Assessment
The 1992 report of the IPCC Scientific Assessment Working Group

Climate Change 1992 - The Supplementary Report to the IPCC Impacts Assessment
The 1992 report of the IPCC Impacts Assessment Working Group

Climate Change: The IPCC 1990 and 1992 Assessments
IPCC First Assessment Report Overview and Policymaker Summaries, and 1992 IPCC Supplement

Global Climate Change and the Rising Challenge of the Sea
Coastal Zone Management Subgroup of the IPCC Response Strategies Working Group, 1992

Report of the IPCC Country Study Workshop, 1992

Preliminary Guidelines for Assessing Impacts of Climate Change, 1992

IPCC Guidelines for National Greenhouse Gas Inventories (3 volumes), 1994

Climate Change 1994 - Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios

IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations
1995

Climate Change 1995 - The Science of Climate Change – Contribution of Working Group I to the Second Assessment Report

Climate Change 1995 - Scientific-Technical Analyses of Impacts, Adaptations and Mitigation of Climate Change - Contribution of Working Group II to the Second Assessment Report

Climate Change 1995 - The Economic and Social Dimensions of Climate Change - Contribution of Working Group III to the Second Assessment Report

The IPCC Second Assessment Synthesis of Scientific-Technical Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change, 1995

Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (3 volumes), 1996

Technologies, Policies and Measuares for Mitigating Climate Change - IPCC Technical Paper 1, 1996

An Introduction to Simple Climate Models Used in the IPCC Second Assessment Report - IPCC Technical Paper 2, 1997

Stabilisation of Atmospheric Greenhouse Gases: Physical, Biological and Socio-Economic Implications - IPCC Technical Paper 3, 1997

Implications of Proposed Co2 Emissions Limitations IPCC Technical Paper 4, 1997

The Regional Impacts of Climate Change: An Assessment of Vulnerability
IPCC Special Report, 1997

Aviation and the Global Atmosphere
IPCC Special Report, 1999

Methodological and Technological Issues in Technology Transfer
IPCC Special Report, 2000

Emissions Scenarios
IPCC Special Report, 2000

Land Use, Land Use Change and Forestry
IPCC Special Report, 2000

Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories
IPCC National Greenhouse Gas Inventories Programme, 2000

Climate Change and Biodiversity - IPCC Technical Paper V, 2002

Climate Change 2001: The Scientific Basis - Contribution of Working Group I to the Third Assessment Report

Climate Change 2001: Impacts, Adaptation & Vulnerability - Contribution of Working Group II to the Third Assessment Report

Climate Change 2001: Mitigation - Contribution of Working Group III to the Third Assessment Report

Climate Change 2001: Synthesis Report

Good Practice Guidance for Land Use, Land-use Change and Forestry
IPCC National Greenhouse Gas Inventories Programme, 2003

Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons
IPCC/TEAP Special Report, 2005

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, policy-makers in governments and environmental organizations, and scientists and engineers in industry.

The Intergovernmental Panel on Climate Change (IPCC) was established jointly by the World Meteorological Organization and the United Nations Environment Programme (UNEP). The Panel provides authoritative international assessments of scientific information on climate change. This report was produced by the IPCC on the invitation of the United Nations Framework Convention on Climate Change.

The full Special Report is published by Cambridge University Press (www.cambridge.org) and the digital version can be accessed via the website of the IPCC Secretariat (www.ipcc.ch), or obtained on CDRom from the IPCC Secretariat. This brochure contains the Summary for Policymakers and the Technical Summary of the report.