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IPCC Special Report

Carbon Dioxide Capture and Storage

Summary for Policymakers

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

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

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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
Total	**7,887**	**13,466**

[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).

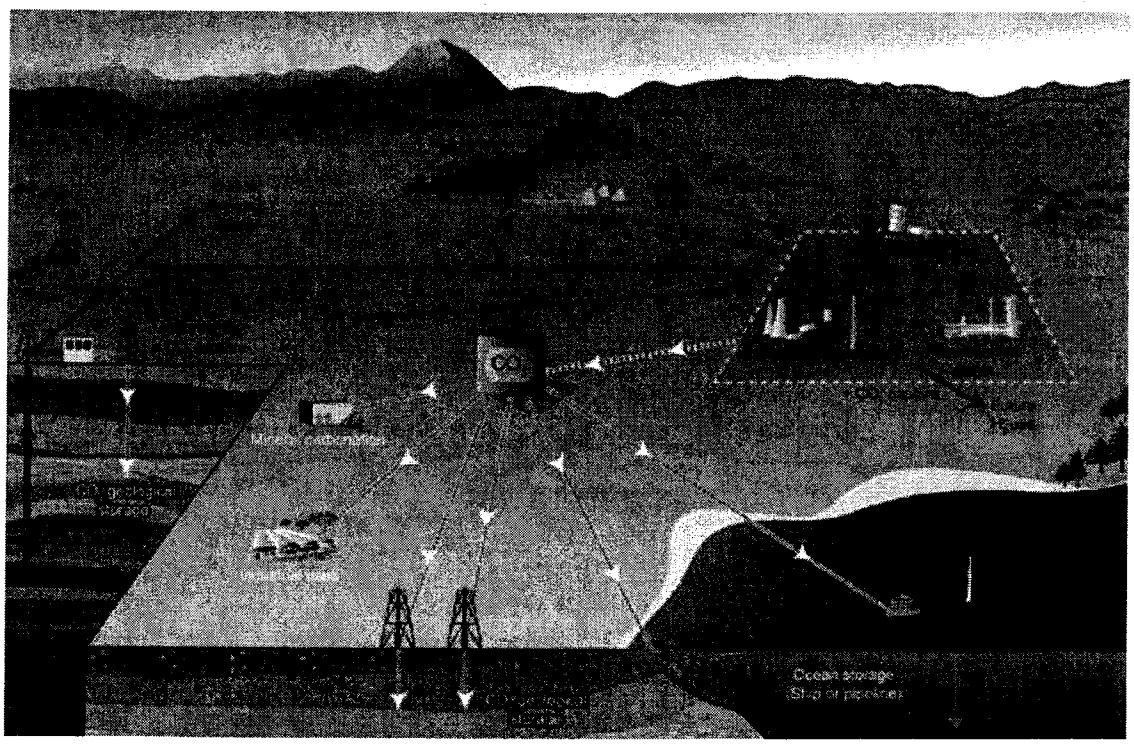

Figure SPM.1. Schematic diagram of possible CCS systems showing the sources for which CCS might be relevant, transport of CO_2 and storage options (Courtesy of CO2CRC).

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–

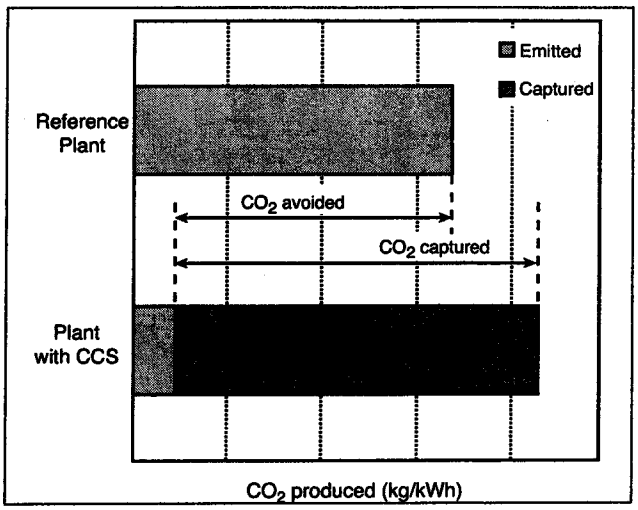

Figure SPM.2. CO_2 capture and storage from power plants. The increased CO_2 production resulting from the loss in overall efficiency of power plants due to the additional energy required for capture, transport and storage and any leakage from transport result in a larger amount of "CO_2 produced per 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-

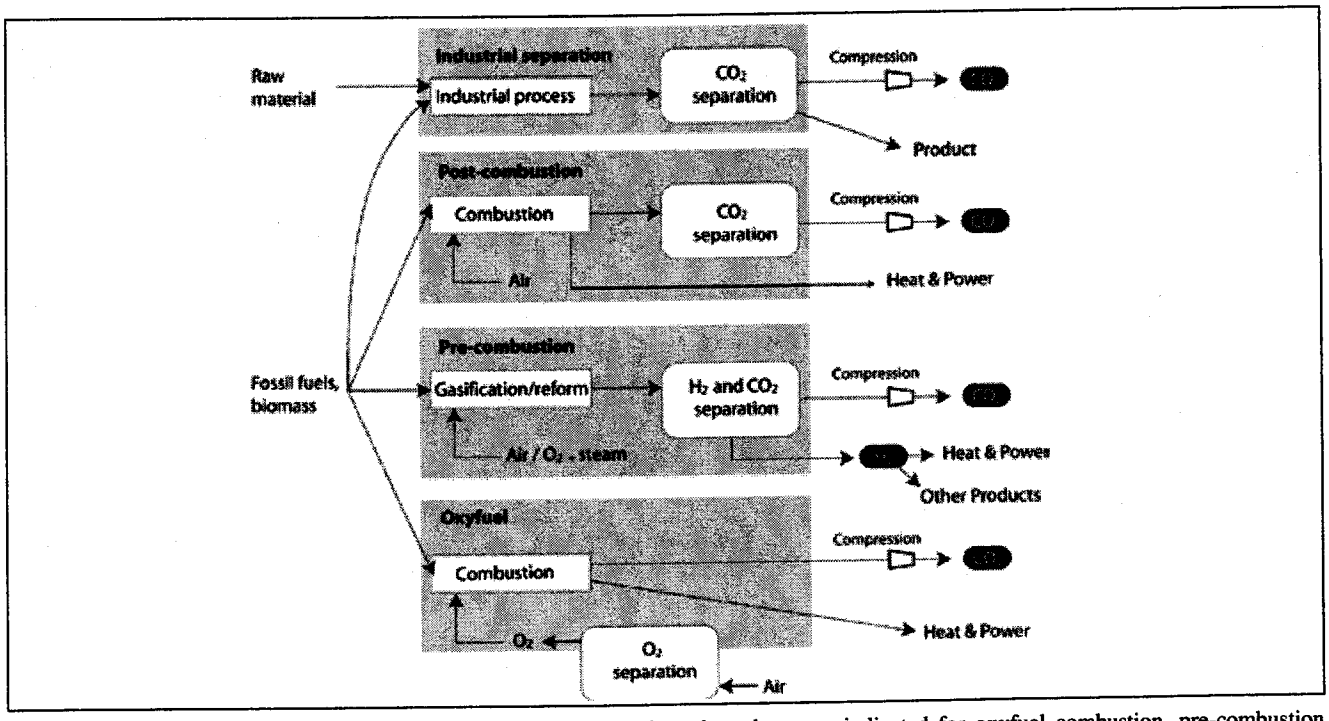

Figure SPM.3. Schematic representation of capture systems. Fuels and products are indicated for oxyfuel combustion, pre-combustion (including hydrogen and fertilizer production), post-combustion and industrial sources of CO_2 (including natural gas processing facilities and steel and cement production)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

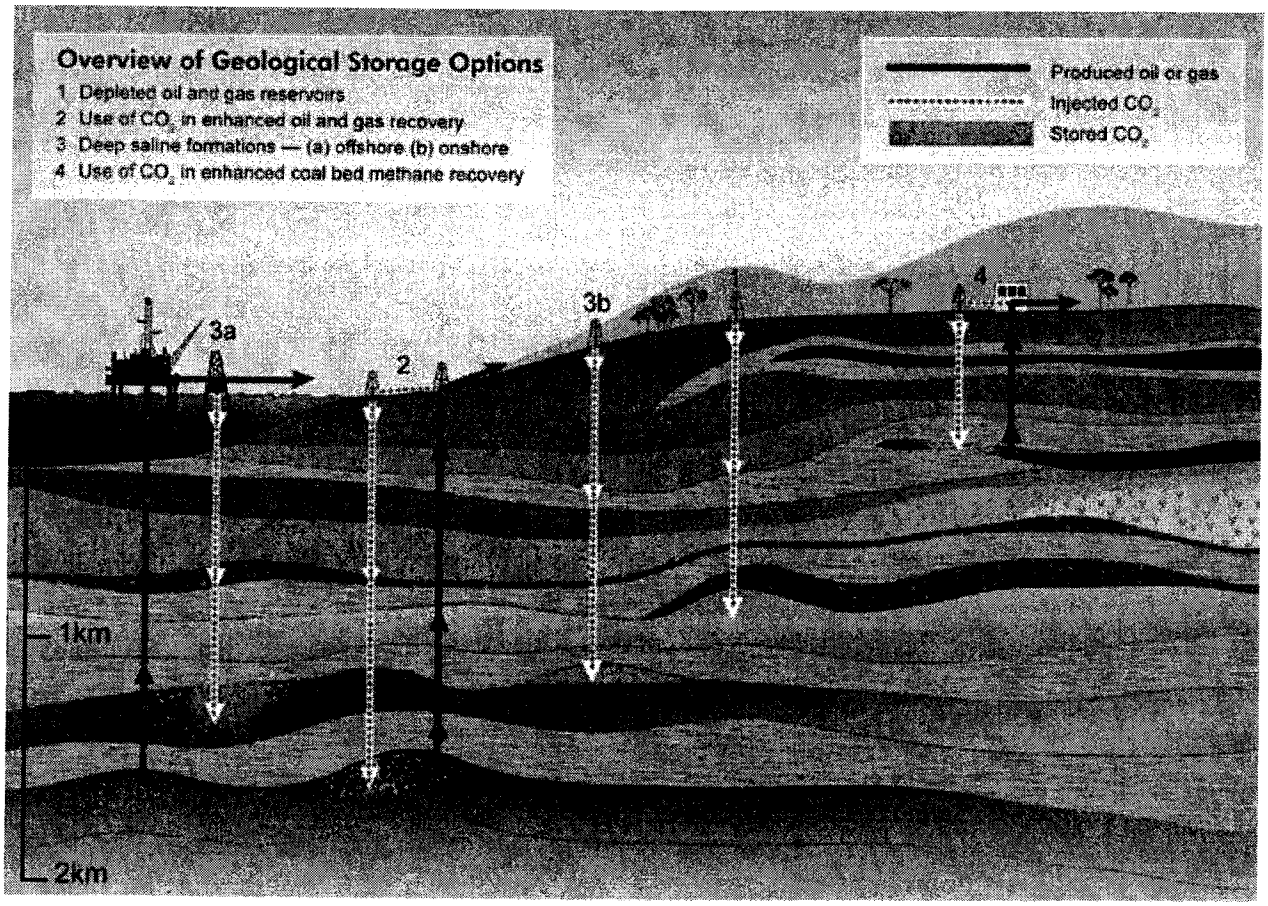

Figure SPM.4. Overview of geological storage options (based on Figure 5.3) (Courtesy CO2CRC).

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.

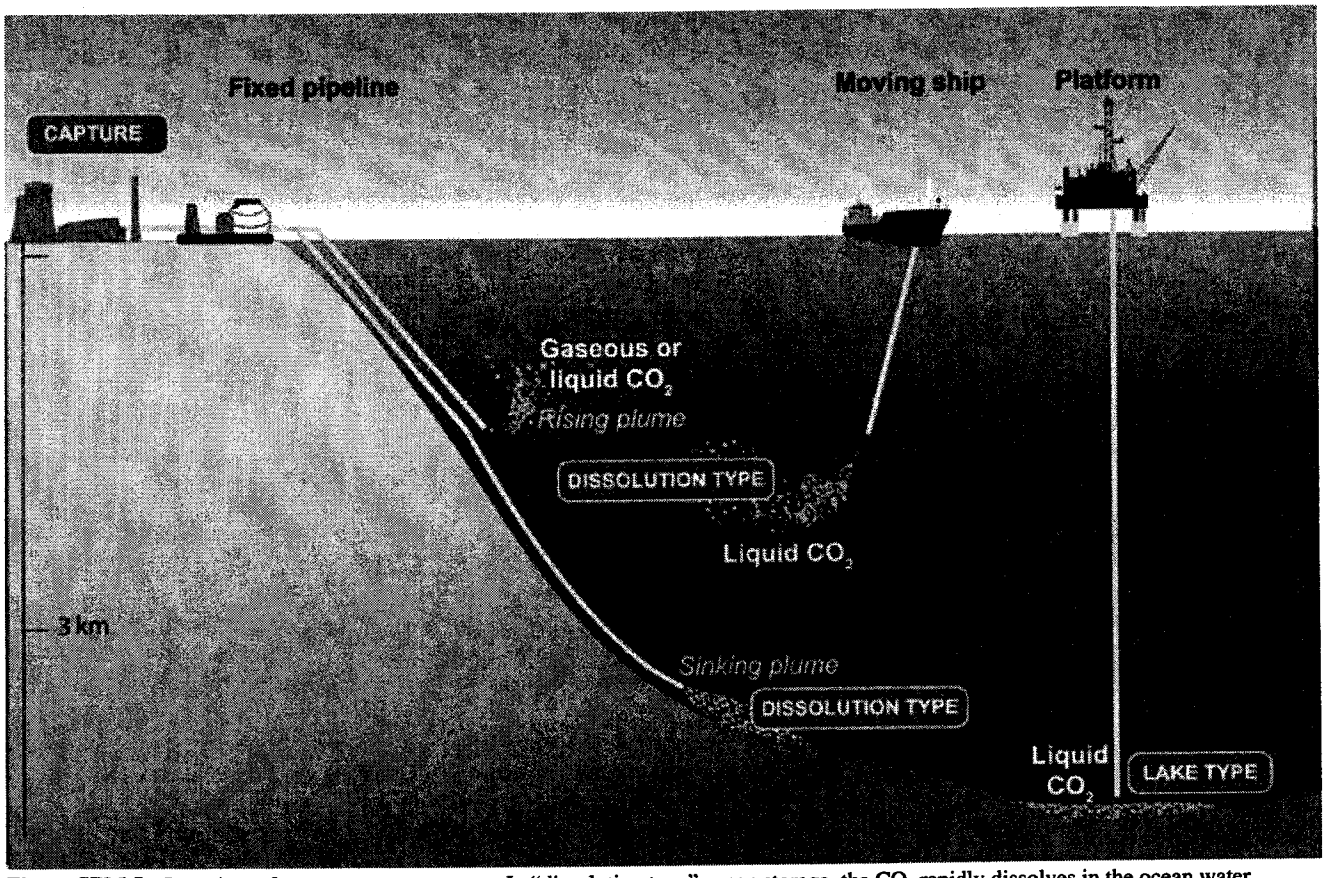

Figure SPM.5. Overview of ocean storage concepts. In "dissolution type" ocean storage, the CO_2 rapidly dissolves in the ocean water, whereas in "lake type" ocean storage, the CO_2 is initially a liquid on the sea floor (Courtesy CO2CRC).

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.

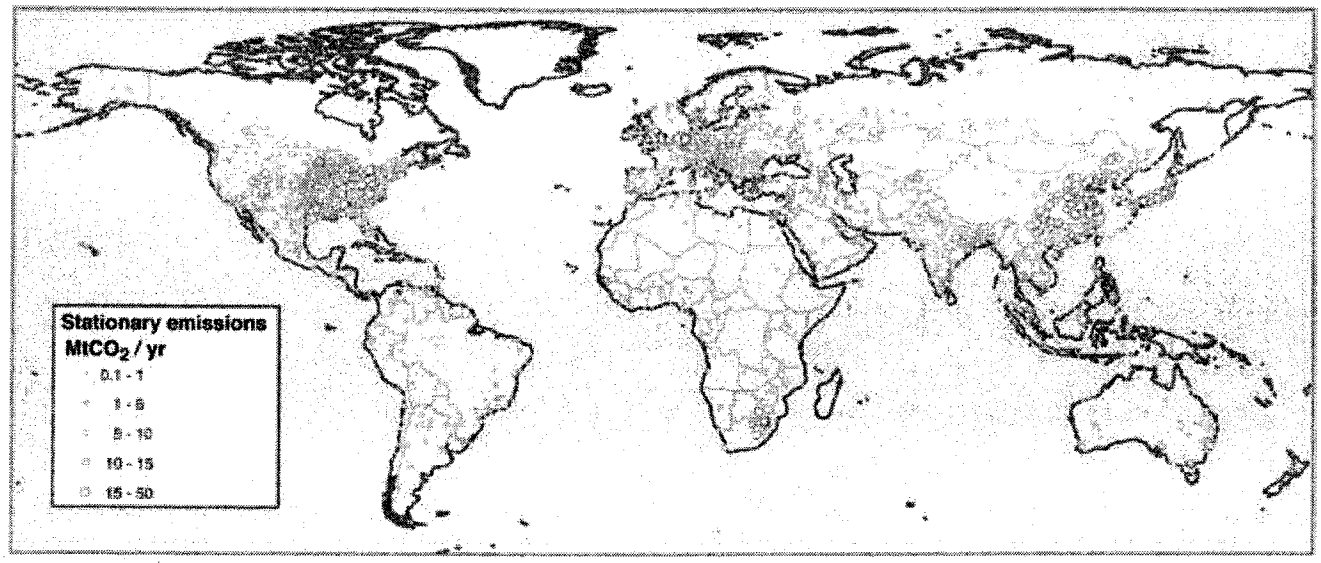

Figure SPM.6a. Global distribution of large stationary sources of CO_2 (Figure 2.3) (based on a compilation of publicly available information on global emission sources; IEA GHG 2002)

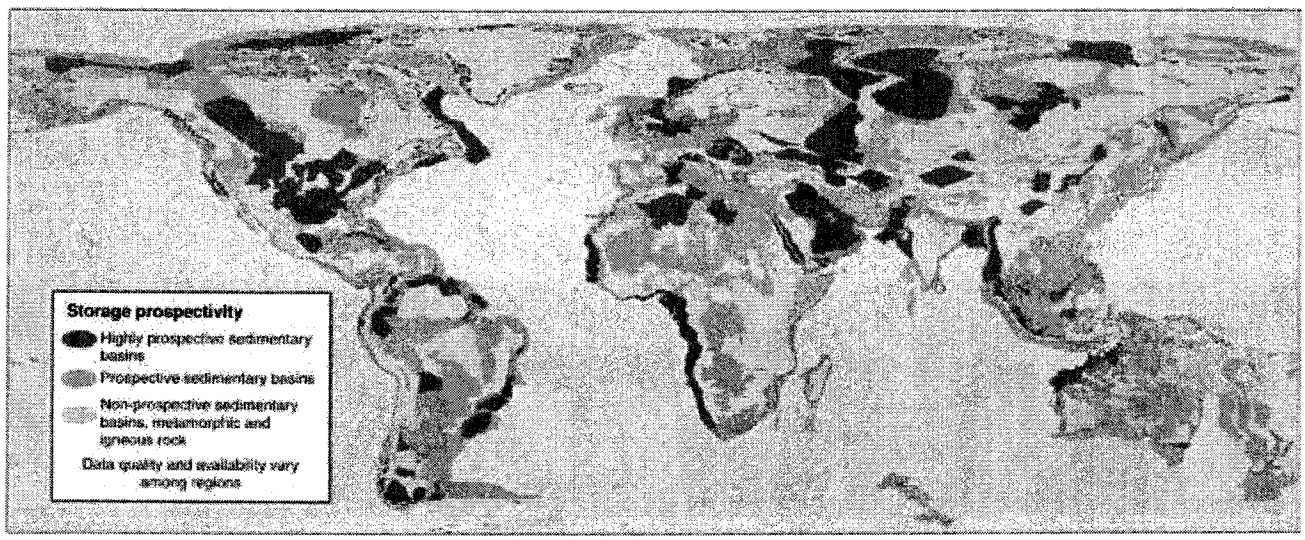

Figure SPM.6b. Prospective areas in sedimentary basins where suitable saline formations, oil or gas fields or coal beds may be found. Locations for storage in coal beds are only partly included. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present in 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 (Section 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$/t$CO_2$ avoided	Pulverized Coal reference plant US$/t$CO_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$/t$CO_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$/t$CO_2$ net captured	Applies to high-purity sources requiring simple drying and compression.
Capture from other industrial sources	25-115 US$/t$CO_2$ net captured	Range reflects use of a number of different technologies and fuels.
Transportation	1-8 US$/t$CO_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$/t$CO_2$ net injected	Excluding potential revenues from EOR or ECBM.
Geological storage: monitoring and verification	0.1-0.3 US$/t$CO_2$ injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements.
Ocean storage	5-30 US$/t$CO_2$ net injected	Including offshore transportation of 100-500 km, excluding monitoring and verification.
Mineral carbonation	50-100 US$/t$CO_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$/t$CO_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.

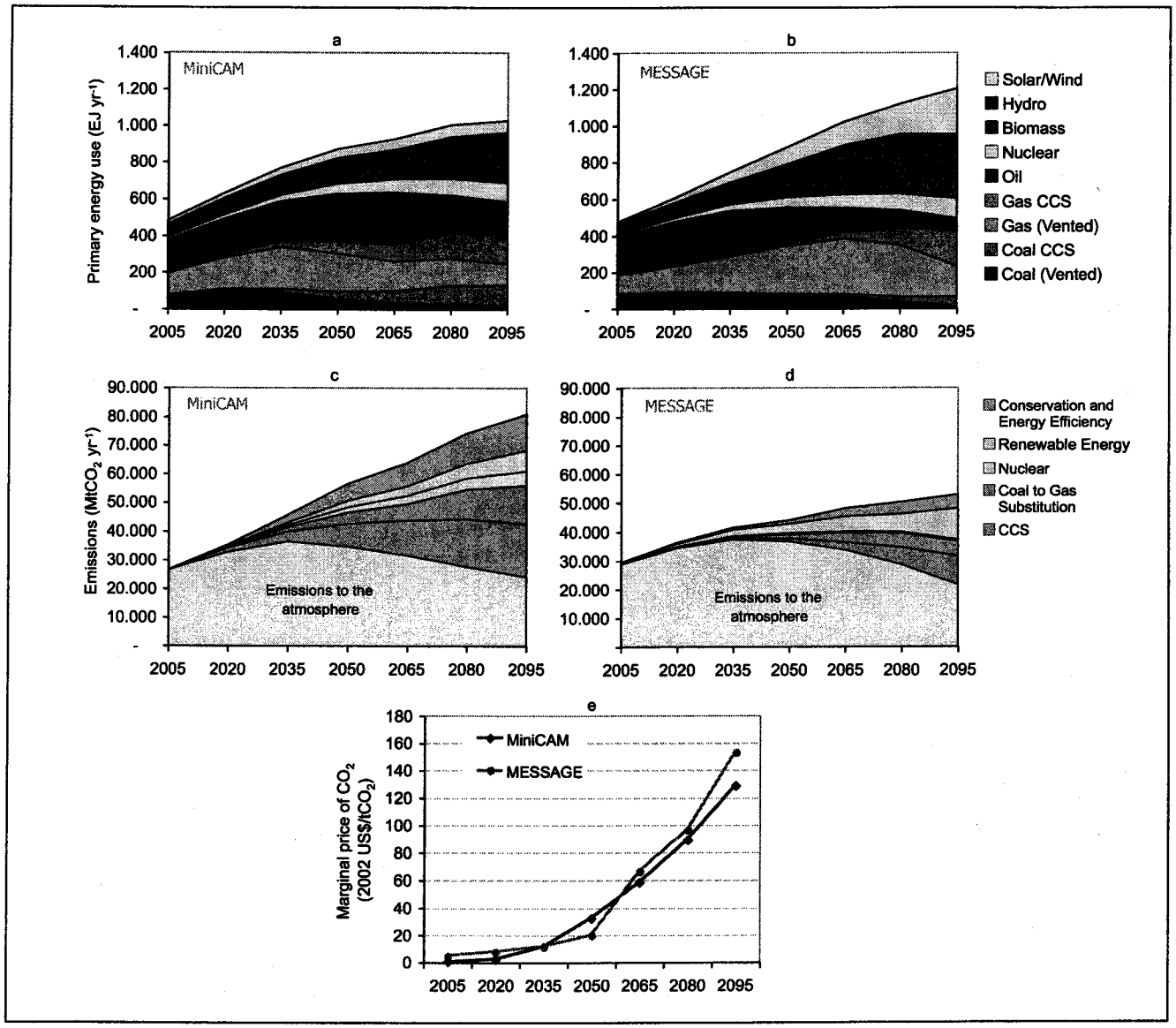

Figure SPM.7. These figures are an illustrative example of the global potential contribution of CCS as part of a mitigation portfolio. They are based on two alternative integrated assessment models (MESSAGE and MiniCAM) while adopt the same assumptions for the main emissions drivers. The results would 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