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 $CO_2$

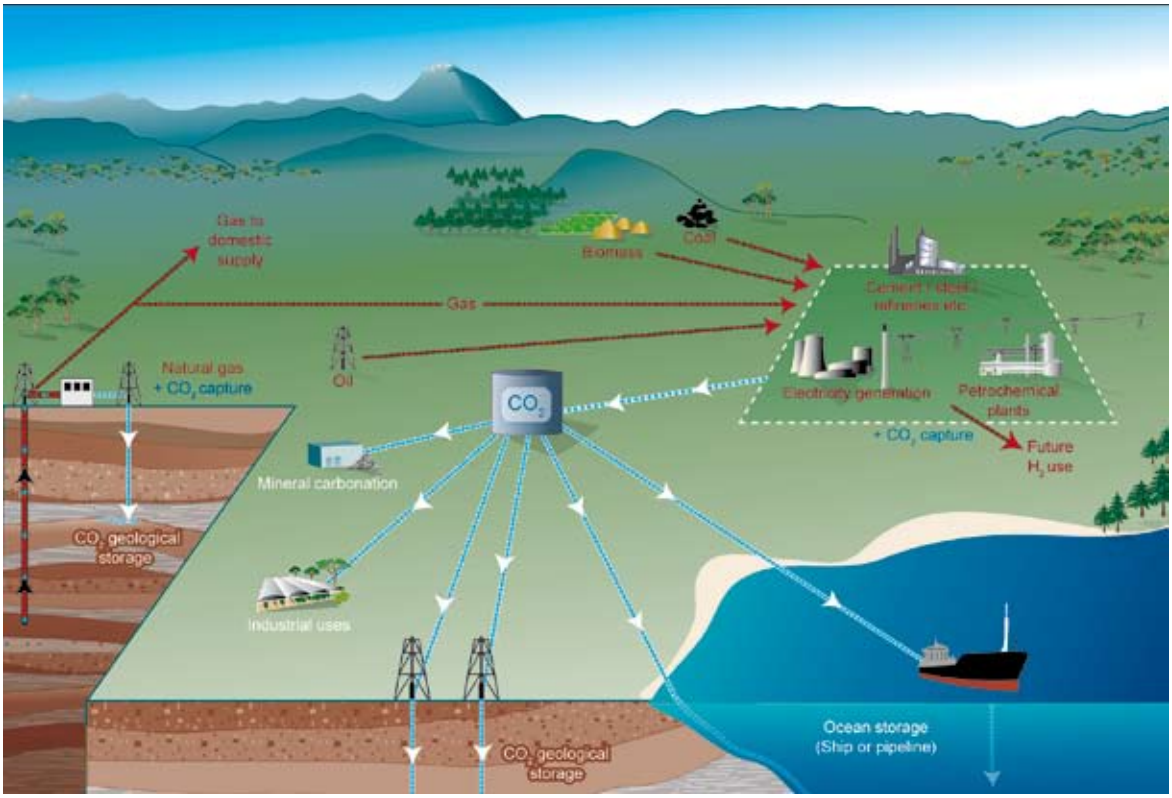


**Figure TS.1.** Schematic diagram of possible CCS systems. It shows the sources for which CCS might be relevant, as well as $CO_2$ transport and storage options (Courtesy CO2CRC).

*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)

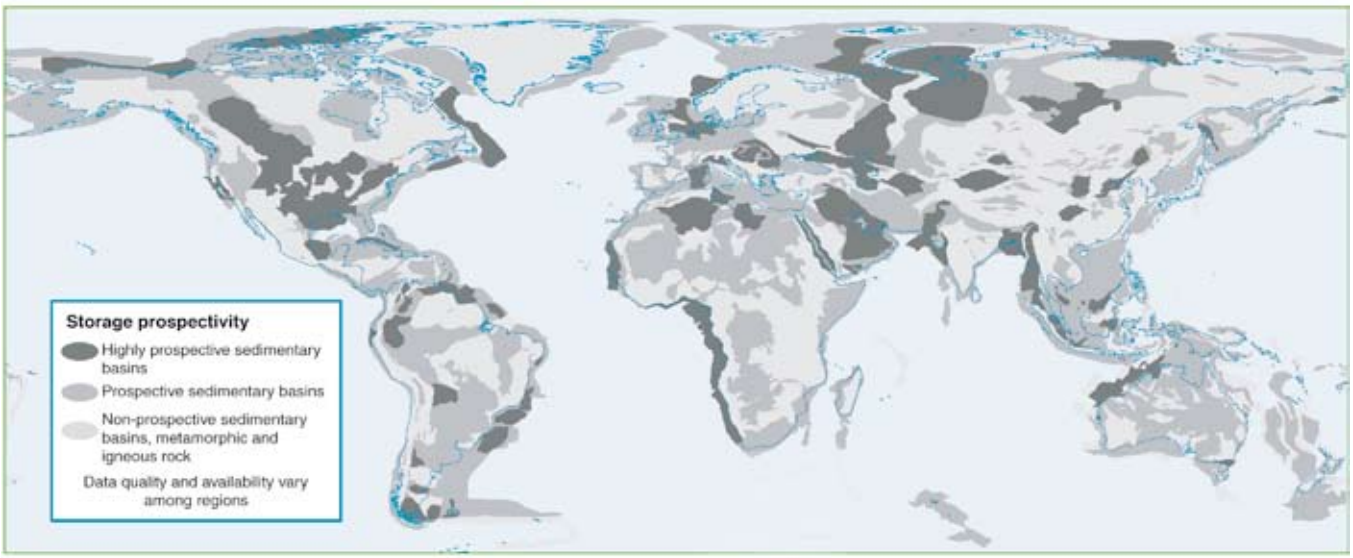


**Figure TS.2b.** Prospective areas in sedimentary basins where suitable saline formations, oil or gas fields, or coal beds may be found. Locations for storage in coal beds are only partly included. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present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

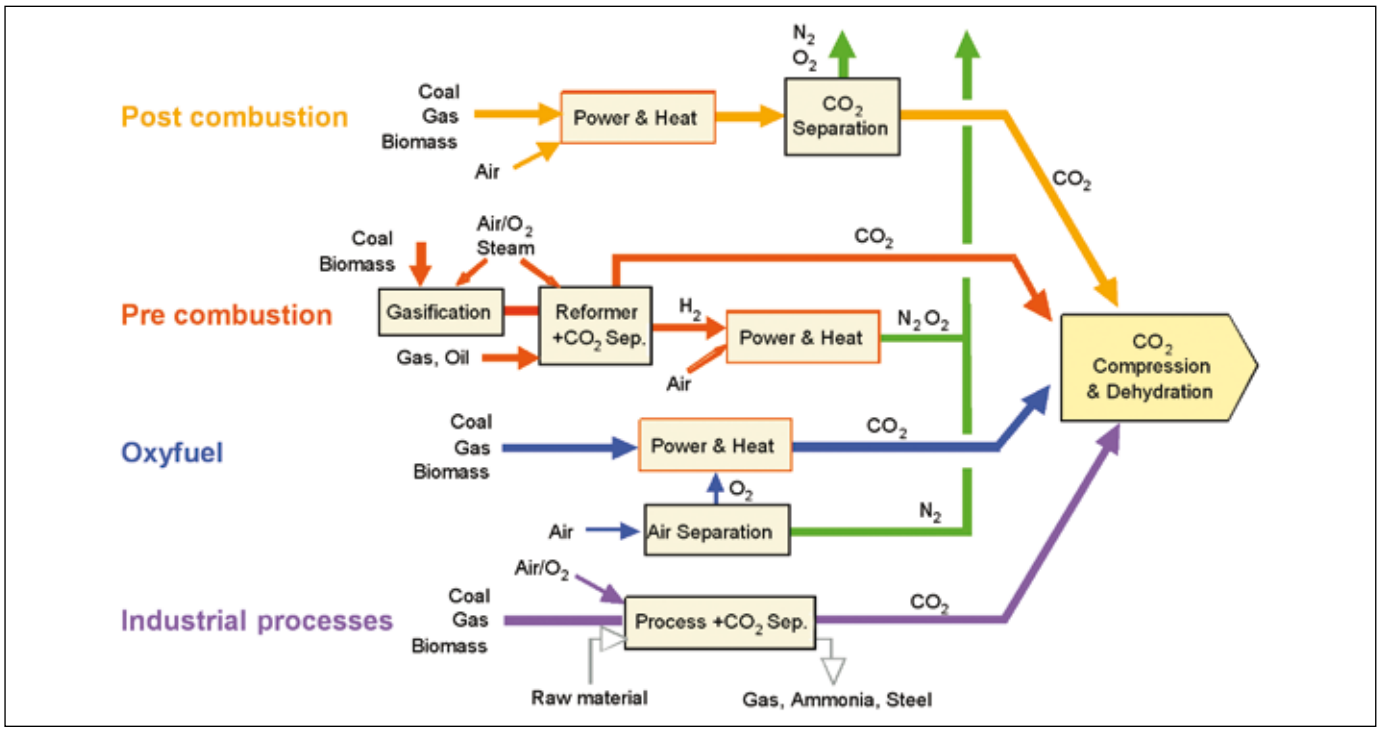


**Figure TS.3**. Overview of $CO_2$ capture processes and systems.

**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 MWe 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$/t$CO_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.

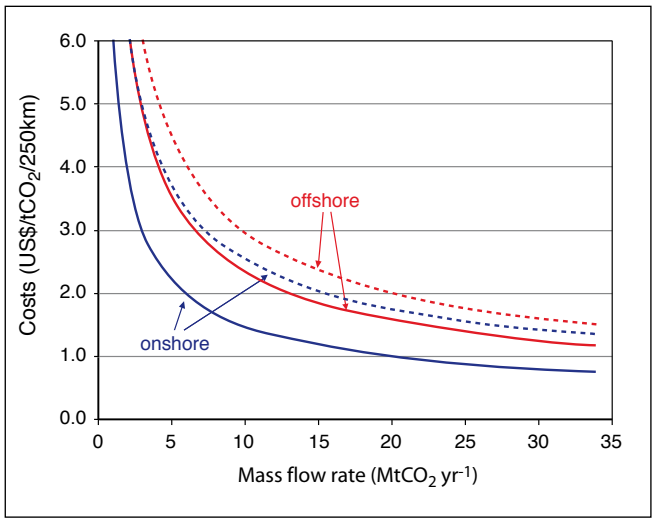


**Figure TS.5.** Transport costs for onshore pipelines and offshore pipelines, in US$ per t$CO_2$ per 250 km as a function of the $CO_2$ mass flow rate. The graph shows high estimates (dotted lines) and low estimates (solid lines).

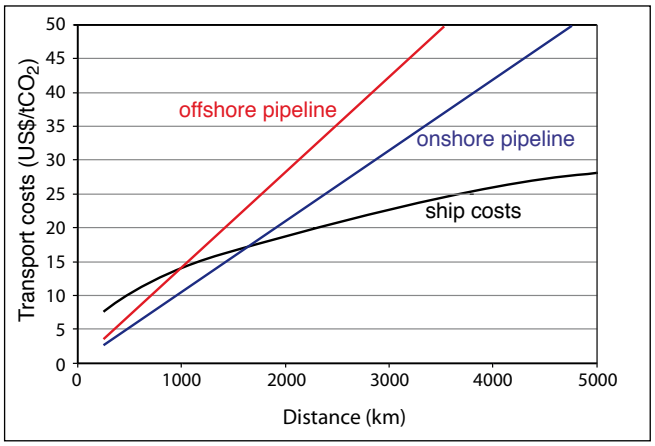


**Figure TS.6.** Costs, plotted as US$/t$CO_2$ transported against distance, for onshore pipelines, offshore pipelines and ship transport. Pipeline costs are given for a mass flow of 6 Mt$CO_2$ $yr^{-1}$. Ship costs include intermediate storage facilities, harbour fees, fuel costs, and loading and unloading 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 Mt$CO_2$ $yr^{-1}$ or more): the Sleipner project in the North Sea, the Weyburn project in Canada and the In Salah project in Algeria. About 3–4 Mt$CO_2$ 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 Mt$CO_2$ 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.

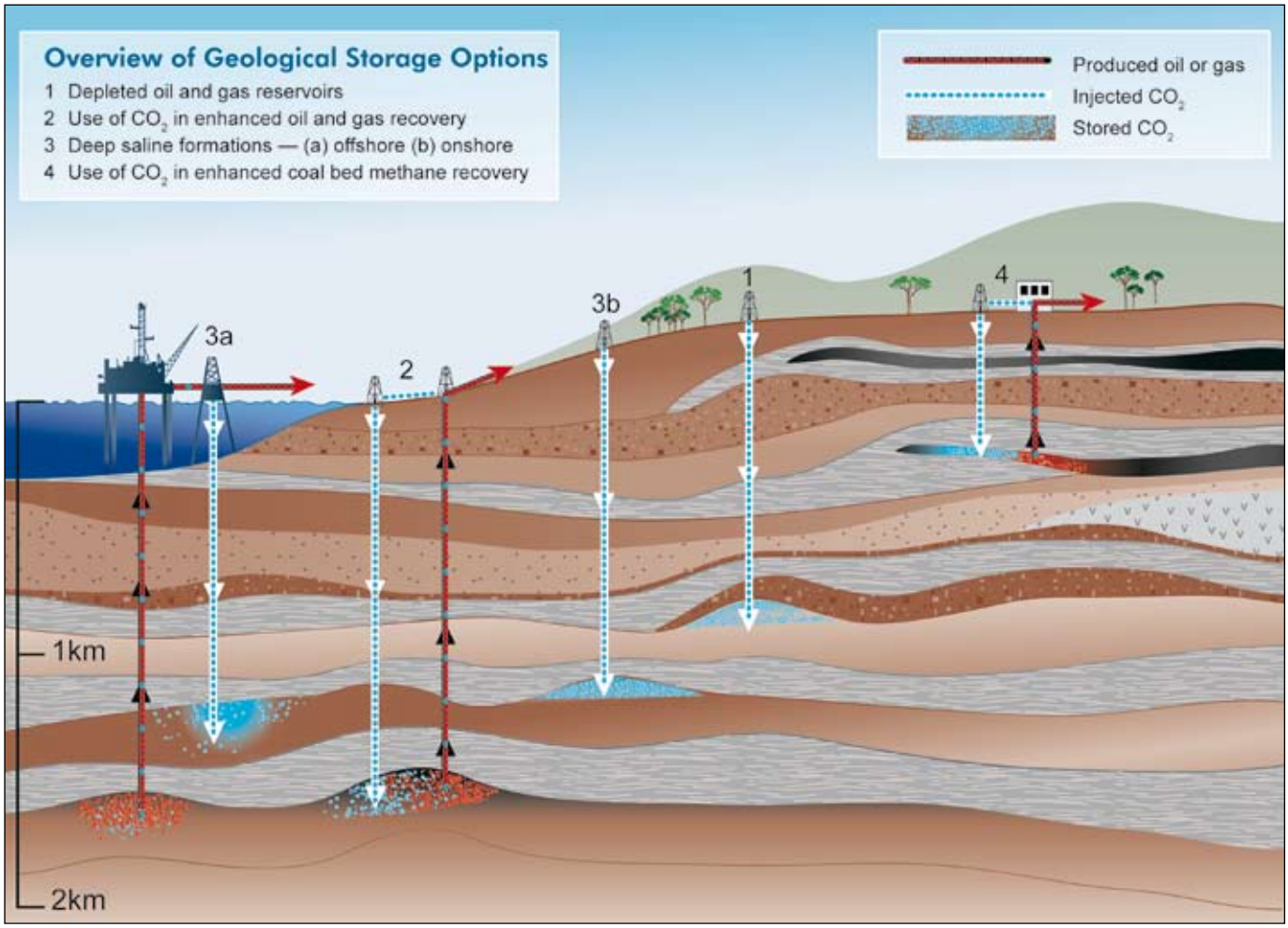


**Figure TS.7.** Methods for storing $CO_2$ in deep underground geological formations. Two methods may be combined with the recovery of hydrocarbons: EOR (2) and ECBM (4). See text for explanation of these methods (Courtesy CO2CRC).

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 $GtCO_2$.

*Site selection criteria and methods*

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

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

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

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

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

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

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

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

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

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

*Risk assessment and environmental impact*

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

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

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

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

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

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

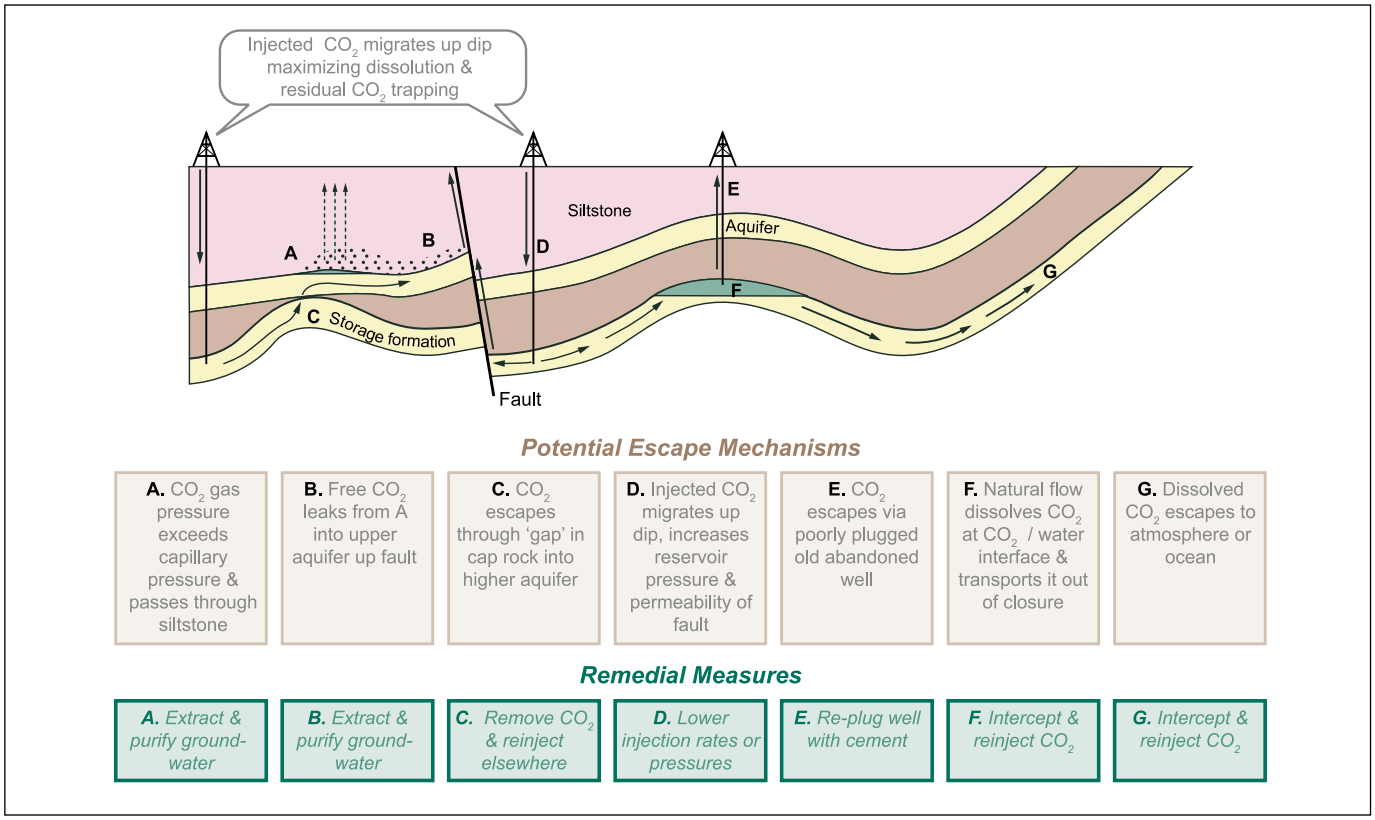


**Figure TS.8.** Potential leakage routes and remediation techniques for $CO_2$ injected into saline formations. The remediation technique would depend on the potential leakage routes identified in a reservoir (Courtesy CO2CRC).

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

*Monitoring and verification*

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

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

*Legal issues*

At present, few countries have specifically developed legal and regulatory frameworks for onshore $CO_2$ storage. Relevant legislation include petroleum-related legislation, drinking-water legislation and mining regulations. In many cases, there are laws applying to some, if not most, of the issues related to $CO_2$ storage. Specifically, long-term liability issues, such as global issues associated with the

leakage of $CO_2$ to the atmosphere, as well as local concerns about environmental impact, have not yet been addressed. Monitoring and verification regimes and risks of leakage may play an important role in determining liability, and vice-versa. There are also considerations such as the longevity of institutions, ongoing monitoring and transferability of institutional knowledge. The long-term perspective is essential to a legal framework for CCS as storage times extend over many generations as does the climate change problem. In some countries, notably the US, the property rights of all those affected must be considered in legal terms as pore space is owned by surface property owners.

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

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

*Public perception*

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

*Cost of geological storage*

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

Representative estimates of the cost for storage in saline formations and depleted oil and gas fields are typically between 0.5–8 US\$/t$CO_2$ injected. Monitoring costs of 0.1–0.3 US\$/t$CO_2$ 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\$/t$CO_2$ (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

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

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

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

## 6. Ocean storage

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

*Storage mechanisms and technology*

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

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

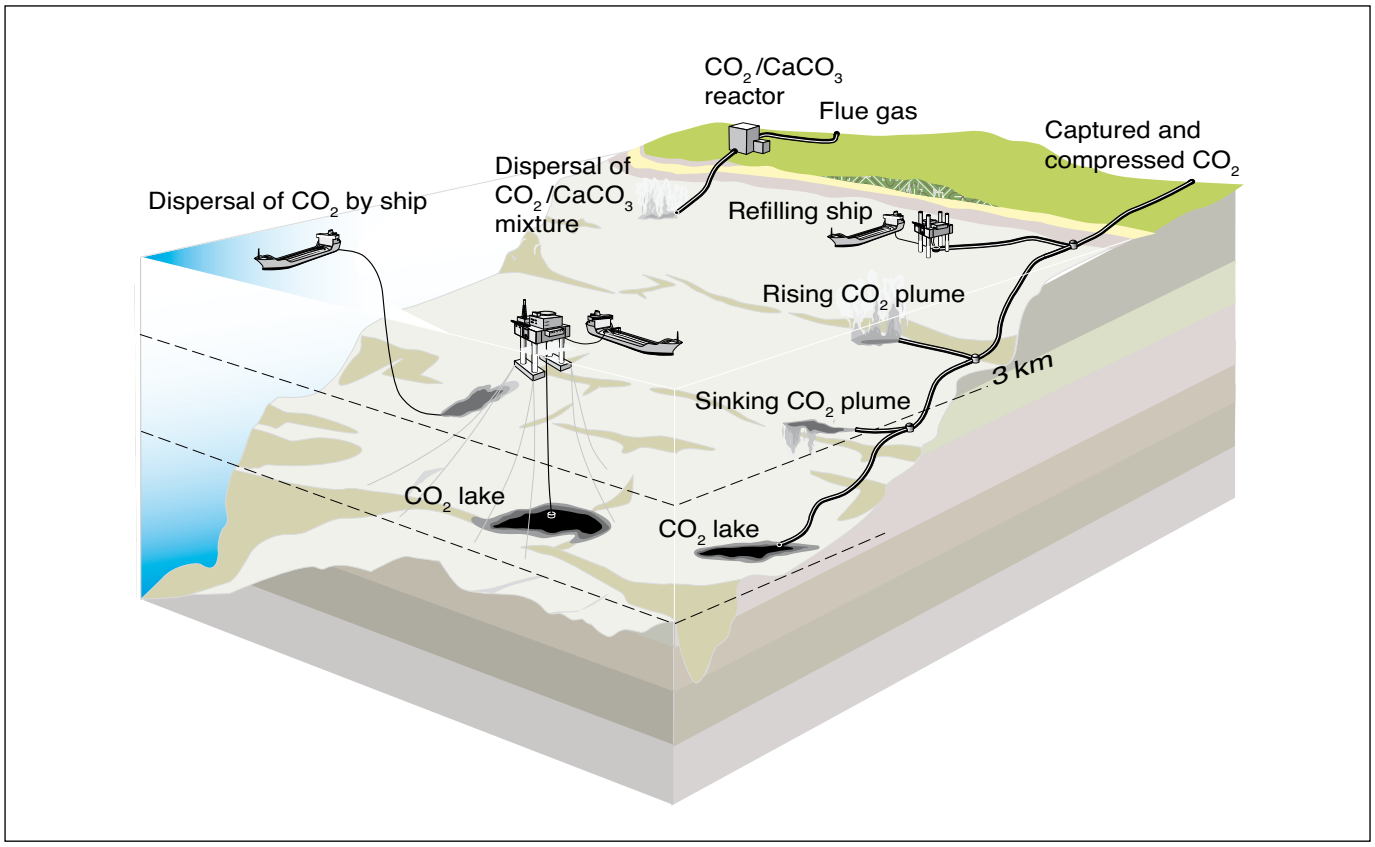


**Figure TS.9.** Methods of ocean storage.

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

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

*Ecological and environmental impacts and risks*

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

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

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

*Costs of ocean storage*

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

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

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

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

| Ocean storage method | Costs (US$/t$CO_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

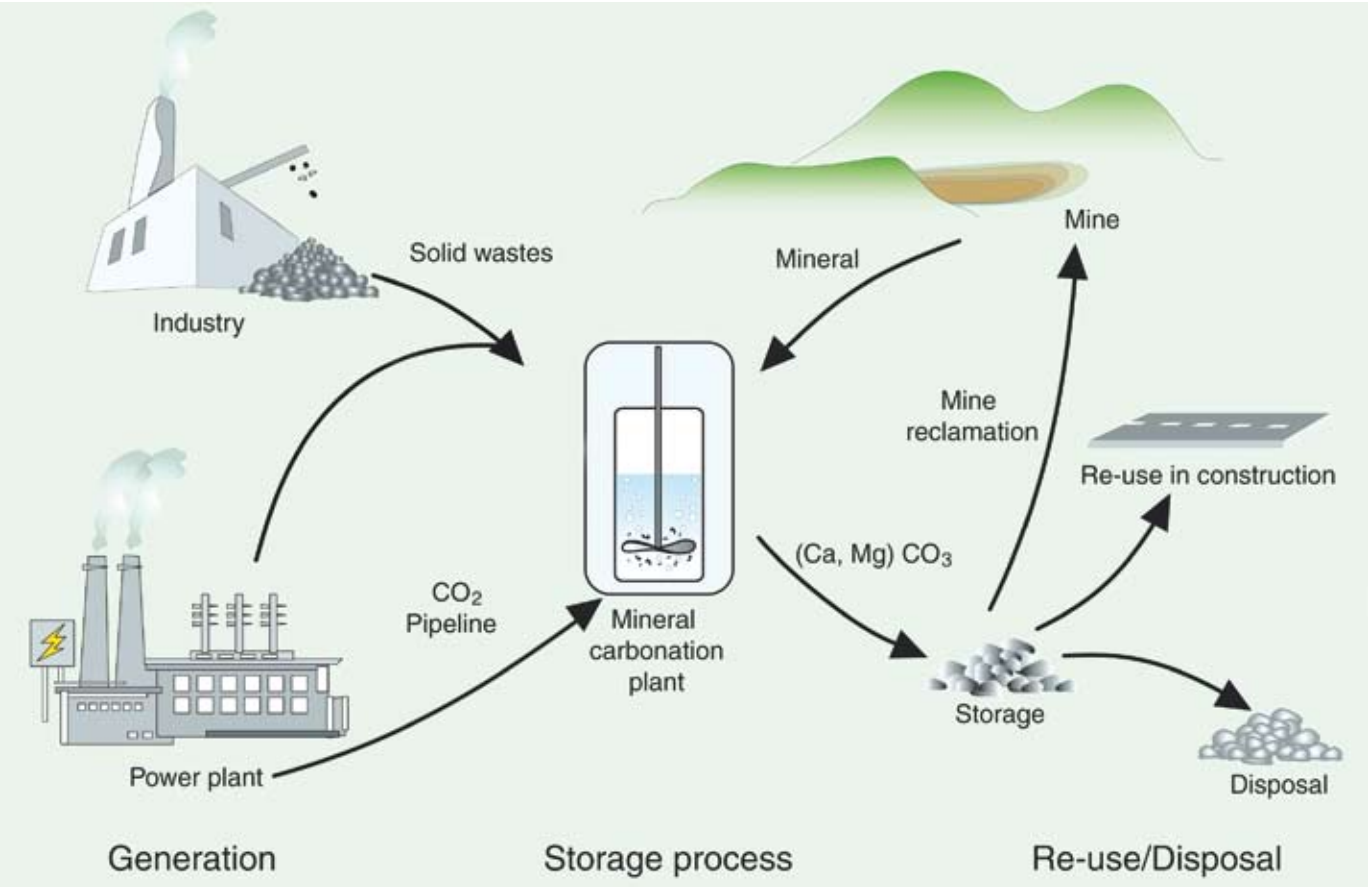


**Figure TS.10.** Material fluxes and process steps associated with the mineral carbonation of silicate rocks or industrial residues (Courtesy ECN).

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$/t$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) Mt$CO_2$ $yr^{-1}$. |
| 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.

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$/t$CO_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$/t$CO_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

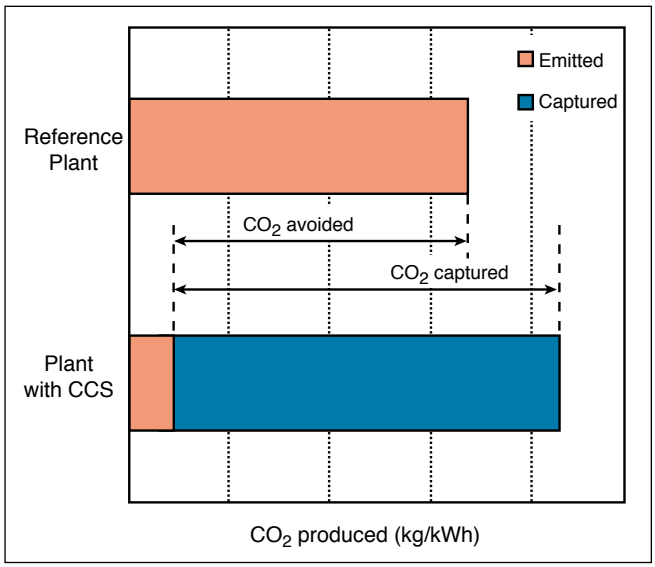


**Figure TS.11.** $CO_2$ capture and storage from power plants. The increased $CO_2$ production resulting from loss in overall efficiency of power plants due to the additional energy required for capture, transport and storage, and any leakage from transport result in a larger amount of "$CO_2$ produced 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 Mt$CO_2$ 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<br>US$/t$CO_2$ avoided<br>(US$/tC avoided) | PC reference plant<br>US$/t$CO_2$ avoided<br>(US$/tC avoided) |
|---|---|---|
| **Power plant with capture and geological storage** | | |
| NGCC | 40 - 90<br>(140 - 330) | 20 - 60<br>(80 - 220) |
| PC | 70 - 270<br>(260 - 980) | 30 - 70<br>(110 - 260) |
| IGCC | 40 - 220<br>(150 - 790) | 20 - 70<br>(80 - 260) |
| **Power plant with capture and EOR** | | |
| NGCC | 20 - 70<br>(70 - 250) | 0 - 30<br>(0 - 120) |
| PC | 50 - 240<br>(180 - 890) | 10 - 40<br>(30 - 160) |
| IGCC | 20 - 190<br>(80 - 710) | 0 - 40<br>(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.

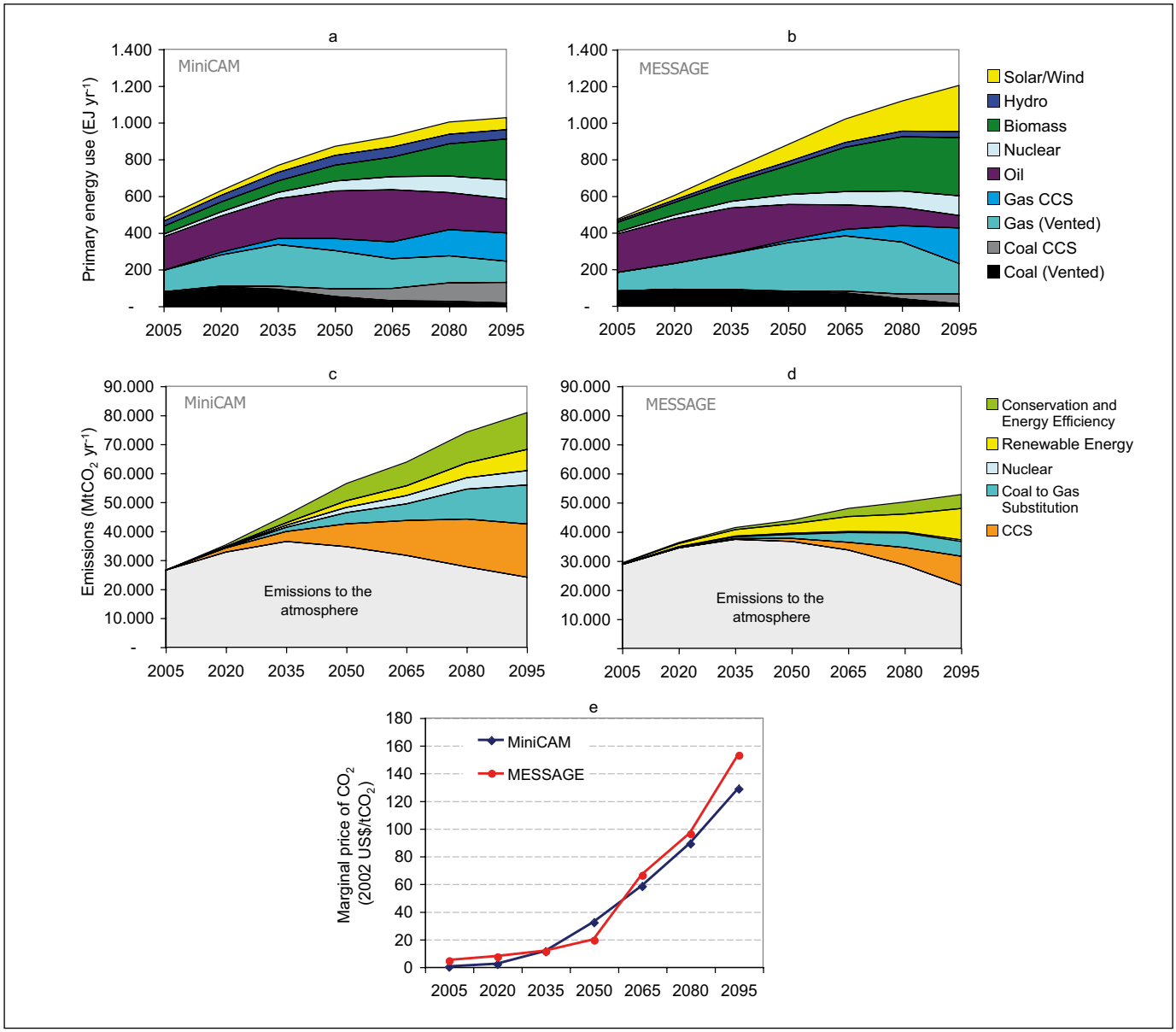


**Figure TS.12.** These figures are an illustrative example of the global potential contribution of CCS as part of a mitigation portfolio. They are based on two alternative integrated assessment models (MESSAGE and MiniCAM) adopting the same assumptions for the main emissions drivers. The results would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