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What is CO₂ capture and storage and how could it contribute to mitigating climate change?

1. *Carbon dioxide (CO₂) capture and storage (CCS) is a process consisting of separation of CO₂ from industrial and energy-related sources, transport to a storage location, and long-term isolation from the atmosphere. This report considers CCS as an option in the portfolio of mitigation actions for stabilization of atmospheric greenhouse gas concentrations.*

Other mitigation options include energy efficiency improvements, the switch to less carbon intensive fuels, nuclear power, renewable energy sources, enhancement of biological sinks, and reduction of non-CO₂ greenhouse gas emissions. CCS has the potential to reduce overall mitigation costs and increase flexibility in achieving greenhouse gas emission reductions. The widespread application of CCS would depend on technical maturity, costs, overall potential, diffusion and transfer of the technology to developing countries and their capacity to apply the technology, regulatory aspects, environmental issues and public perception (Sections 1.1.1, 1.3, 1.7, 8.3.3.4).

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

Most scenarios project that the supply of primary energy will continue to be dominated by fossil fuels until at least the middle of the century. As discussed in the TAR, most models also indicate that known technological options¹ could achieve a broad range of atmospheric stabilization levels, but implementation would require socio-economic and institutional changes. In this context, the availability of CCS in the portfolio of options could facilitate achieving stabilization goals (Sections 1.1, 1.3, 1.6.6).

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

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What are the characteristics of CCS?

3. *Capture of CO₂ can be applied to large point sources. The CO₂ would then be compressed and transported for storage in geological formations, in the ocean, in mineral carbonates², or for use in industrial processes.*

Large point sources of CO₂ include large fossil fuel or biomass energy facilities, major CO₂-emitting industries, natural gas production, synthetic fuel plants and fossil fuel-based hydrogen production plants (see Table S.1). Potential technical storage methods are: geological storage (in geological formations, such as oil and gas fields, unminable coal beds and deep saline formations³), ocean storage (direct release into the ocean water column or onto the deep seafloor) and industrial fixation of CO₂ into inorganic carbonates. This report also discusses industrial uses of CO₂, but this is not expected to contribute much to reduction of CO₂ emissions (see Figure S.1) (Sections 1.2, 1.4, 2.2, 2.5.2, Table 2.3).

Table S.1. Profile by process or industrial activity of worldwide large stationary CO₂ sources with emissions of more than 0.1 million tonnes of CO₂ (MtCO₂) per year.

| Process | No. of sources | Emissions (MtCO ₂ /yr) |
|-----------------------------------|----------------|-----------------------------------|
| Fossil Fuels | | |
| Power (coal, gas, oil and others) | 4,942 | 10,539 |
| Cement production | 1,175 | 932 |
| Refineries | 638 | 798 |
| Iron and steel industry | 269 | 646 |
| Petrochemical industry | 470 | 379 |
| Oil and gas processing | Not available | 50 |
| Other sources | 90 | 33 |
| Biomass | | |
| Bioethanol and bioenergy | 303 | 91 |
| Total | 7,887 | 13,466 |

² Storage of CO₂ as mineral carbonates does not cover deep geological carbonation or ocean storage with enhanced carbonate neutralization as discussed in Chapter 6.

³ Saline formations are sedimentary rocks saturated with formation waters containing high concentrations of dissolved salts. They are widespread and contain enormous quantities of water that are unsuitable for agriculture or human consumption. Because the use of geothermal energy is likely to increase, potential geothermal areas may not be suitable for CO₂ storage (see 5.3.3).

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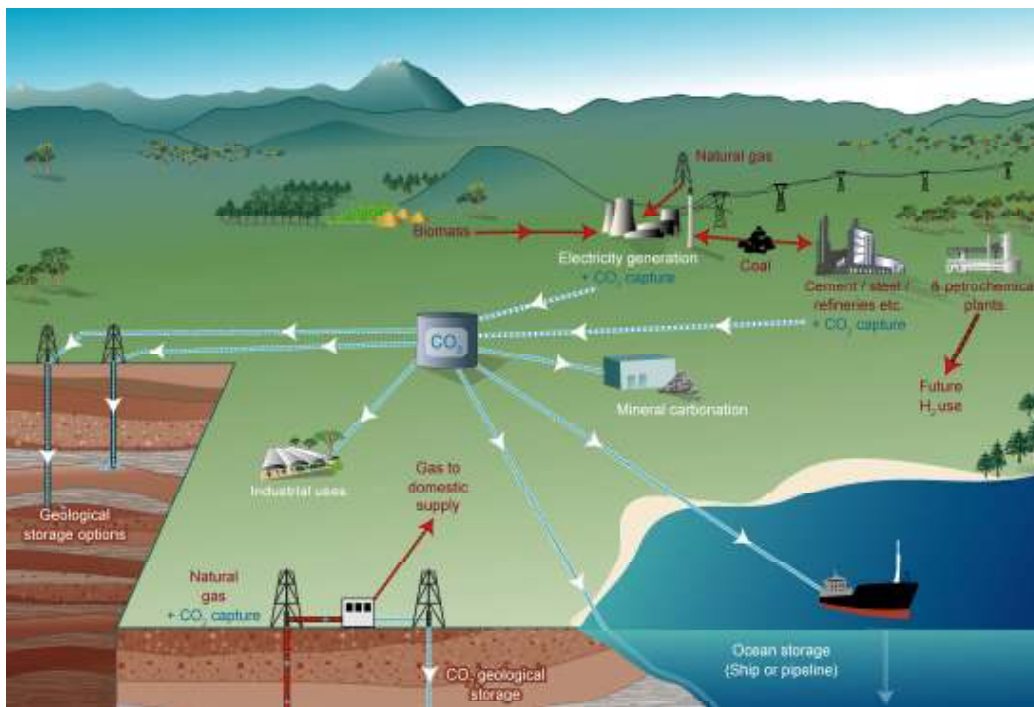


Figure S.1. Schematic diagram of possible CCS systems. It shows the sources for which CCS might be relevant, transport of CO₂, and storage options (Courtesy of CO2CRC).

Agreed changes to the figure:

- Have all fuels (also oil) going into the respective plants

4. *The net reduction of emissions to the atmosphere through CCS depends on the fraction of CO₂ captured, the increased CO₂ production resulting from loss in overall efficiency of power plants or industrial processes due to the additional energy required for capture, transport and storage, any leakage from transport, and the fraction of CO₂ retained in storage over the long term.*

Available technology captures about 85 - 95% of the CO₂ processed in a capture plant. A power plant equipped with a CCS system (with access to geological or ocean storage) would need roughly 10 - 40%⁴ more energy than a plant of equivalent output without CCS, most of it for capture and compression. For secure storage, the net result is that a power plant with CCS could reduce CO₂ emissions to the atmosphere by approximately 80 - 90% compared to a plant without CCS (see Figure S.2). To the extent that leakage might occur from a storage reservoir, the fraction retained is defined as the fraction of the cumulative amount of injected CO₂ that is retained over a specified period of time. CCS systems with storage as

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

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mineral carbonates, would need 60 - 180% more energy than a plant of equivalent output without CCS. (Sections 1.4.4, 1.5.1, 1.6.3, 7.2, Table 3.15).

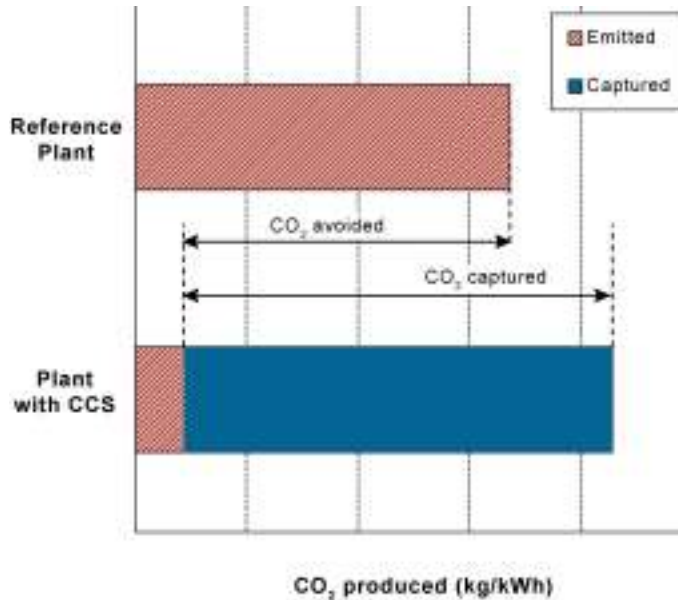


Figure S.2. CO₂ capture and storage from power plants. The increased CO₂ production resulting from loss in overall efficiency of power plants due to the additional energy required for capture, transport and storage, and any leakage from transport result in a larger amount of “CO₂ produced per unit of product”(lower bar relative to the reference plant (upper bar) without capture (Figure 8.2).

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What is the current status of CCS technology?

5. *There are different types of CO₂ capture systems: post-combustion, pre-combustion and oxyfuel combustion (Figure S.3). The concentration of CO₂ in the gas stream, the pressure of the gas stream and the fuel type (solid or gas) are important factors in selecting the capture system.*

Post-combustion capture of CO₂ in power plants is economically feasible under specific conditions⁵; it is used to capture CO₂ from part of the flue gases from a number of existing power plants. Separation of CO₂ in the natural gas processing industry, which uses similar technology, operates in a mature market⁶. The technology required for pre-combustion capture is widely applied in fertilizer manufacturing and in hydrogen production. Although the initial fuel conversion steps of pre-combustion are more elaborate and costly, the higher concentrations of CO₂ in the gas stream, and the higher pressure make the separation easier. Oxyfuel combustion is in the demonstration phase⁷ and uses high purity oxygen. This results in high CO₂ concentrations in the gas stream, and hence in easier separation of CO₂, and in increased energy requirements in the separation of oxygen from air (Sections 3.3, 3.4, 3.5).

⁵ "Economically feasible under specific conditions" means that the technology is well understood and used in selected commercial applications, such as in case of a favourable tax regime or a niche market, processing at least 0.1 MtCO₂/yr, with few (less than 5) replications of the technology.

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

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

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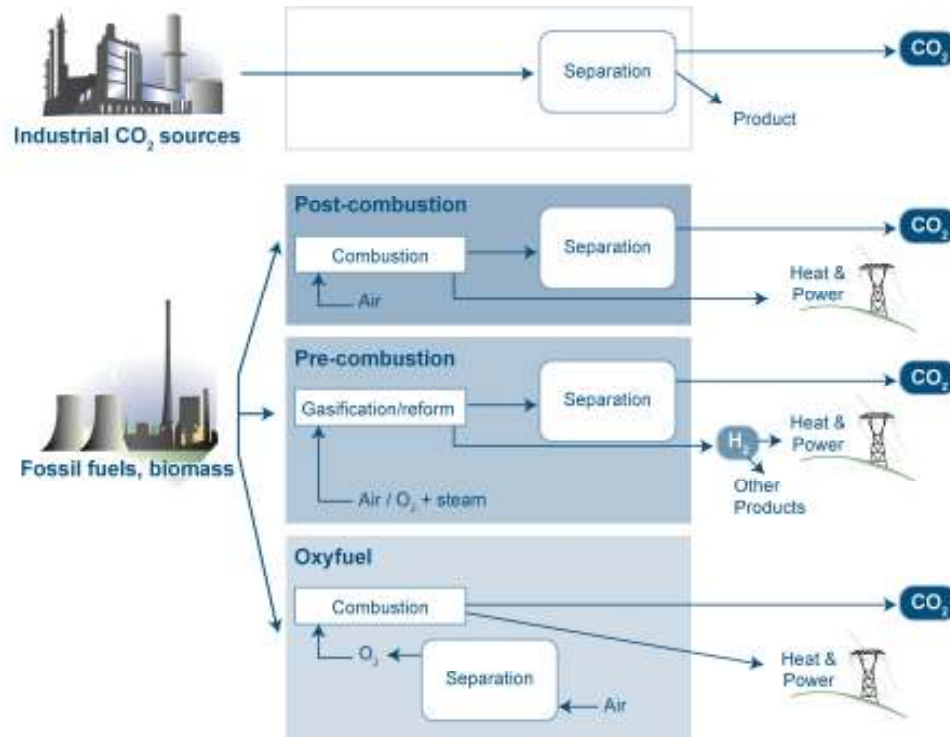


Figure S.3. Schematic representation of capture systems. Fuels and products are indicated for oxyfuel combustion, pre-combustion (including hydrogen and fertilizer production), post-combustion and industrial sources of CO₂ (including natural gas processing facilities, steel and cement production) (Courtesy CO2CRC).

Agreed changes to the figure:

- Arrow leading to H₂ in the pre-combustion block should originate from the "Separation" field.
 - Remove all symbols
 - Specify text in separation boxes
 - Add compression
6. Pipelines are preferred for transporting large amounts of CO₂ for distances up to around 1,000 km. For amounts smaller than a few million tonnes of CO₂ per year, or larger distances overseas, use of ships, where applicable, could be economically more attractive.

Pipeline transport of CO₂ operates as a mature market technology (in the US over 2,500 km of pipelines transport more than 40 MtCO₂ per year). In most gas pipelines, compressors at the upstream end drive the flow, but some pipelines need intermediate compressor stations. Dry CO₂ is not corrosive to pipelines, even if the CO₂ contains contaminants. Where the CO₂ contains moisture, it is removed from the CO₂ stream to prevent corrosion and to avoid the costs of constructing pipelines of corrosion-resistant material. Shipping of CO₂, analogous to shipping

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of liquefied petroleum gases, is economically feasible under specific conditions, but is currently done on a small scale due to limited demand. CO₂ can also be carried by rail and road tankers, but it is unlikely that they could be attractive options for large-scale CO₂ transportation. (Sections 4.2.1, 4.2.2, 4.3.2, 4.3.3).

7. *Storage of CO₂ in deep, onshore or offshore, geological formations uses many of the same technologies that have been developed by the oil and gas industry and has been proven to be economically feasible under specific conditions for oil and gas fields and saline formations, but not yet for storage in unminable coal beds⁸ (see Figure S.4).*

If CO₂ is injected into suitable saline formations or oil or gas fields, at depths below 800m⁹, various physical and geochemical trapping mechanisms would prevent it from migrating to the surface. In general, an essential physical trapping mechanism is the presence of a caprock¹⁰. Coal bed storage may take place at shallower depths and relies on the adsorption of CO₂ on the coal, but the technical feasibility largely depends on the permeability of the coal bed. The combination of CO₂ storage with Enhanced Oil Recovery (EOR¹¹) or, potentially, Enhanced Coal Bed Methane recovery (ECBM) could lead to additional revenues from the oil or gas recovery. Well-drilling technology, injection technology, computer simulation of storage reservoir performance, and monitoring methods from existing applications are being developed further for design and operation of geological storage projects.

Three industrial-scale¹² storage projects are in operation: the Sleipner project in an offshore saline formation in Norway, the Weyburn EOR project in Canada, and the In Salah project in a gas field in Algeria. Others are planned. (Sections 5.1.2, 5.6, Boxes 5.1, 5.2, 5.3, 5.4, 5.5).

⁸ A coal bed that is unlikely to ever be mined because it is too deep or too thin, may be potentially used for CO₂ storage. If subsequently mined, the stored CO₂ would be released. Enhanced Coal Bed Methane (ECBM) recovery could potentially increase methane production from coals while simultaneously storing CO₂. The produced methane would be used and not released to the atmosphere.

⁹ At depths below 800 – 1000 m, CO₂ becomes supercritical and has a liquid-like density (about 500 - 800 kg/m³) that provides the potential for efficient utilization of underground storage space and improves storage security.

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

¹¹ For the purposes of this report, EOR means CO₂-driven Enhanced Oil Recovery.

¹² "Industrial-scale" here means on the order of 1 MtCO₂ per year.

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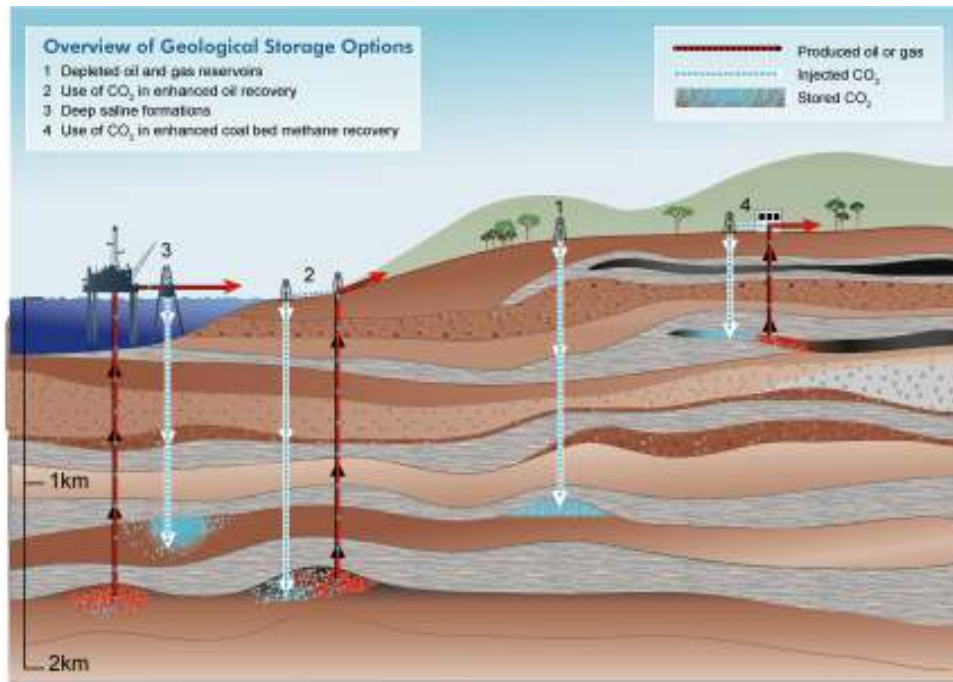


Figure S.4. Overview of geological storage options (Courtesy CO2CRC) (Figure 5.3)

Agreed changes to the figure:

- Add Enhanced Gas Recovery
 - Include saline formation injection onshore
8. *Ocean storage potentially could be done in two ways: by injecting and dissolving CO₂ into the water column (typically below 1,000 meters) via a fixed pipeline or a moving ship, or by depositing it via a fixed pipeline or an offshore platform on the sea floor at depths below 3,000 m, where CO₂ is denser than water and is expected to form a “lake” that would delay dissolution of CO₂ into the surrounding environment (see Figure S.5). Ocean storage and its ecological impacts are still in the research phase¹³.*

The dissolved and dispersed CO₂ would become part of the global carbon cycle and eventually equilibrate with the CO₂ in the atmosphere. In laboratory experiments, small-scale ocean experiments and model simulations, the technologies and associated physical and chemical phenomena, notably increases in acidity (lower pH) and its effect on marine ecosystems, have been studied for a range of ocean storage options (Sections 6.1, 6.1.2, 6.2.1.2, 6.5, 6.7).

¹³ "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.

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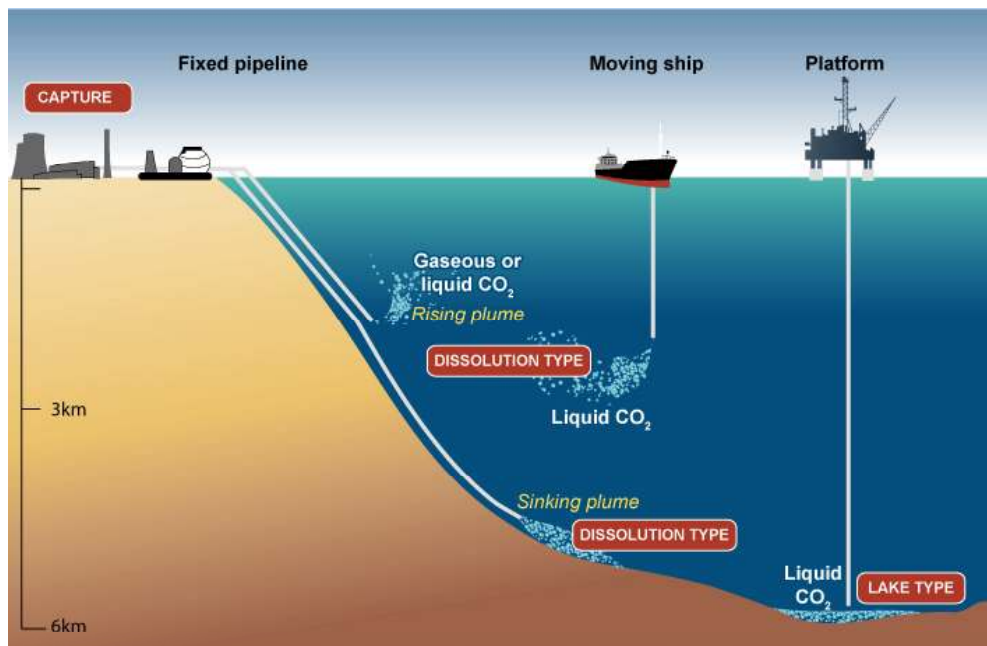


Figure S.5. Overview of ocean storage concepts. In "dissolution type" ocean storage, the CO₂ rapidly dissolves in the ocean water, whereas in "lake type" ocean storage, the CO₂ is initially a liquid on the sea floor (Courtesy CO2CRC).

Agreed change:

- Correctness of the depth scale on the left will be checked, and the scale will be adjusted if necessary

9. *The reaction of CO₂ with metal oxides, which are abundant in silicate minerals and available in small quantities in waste streams, produces stable carbonates. The technology is currently in the research stage, but certain applications in using waste streams are in the demonstration phase.*

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

10. *Industrial uses¹⁴ of captured CO₂ as gas or liquid, or as a feedstock in chemical processes that produce valuable carbon-containing products are possible, but are not expected to contribute to significant abatement of CO₂ emissions.*

The potential for industrial uses of CO₂ is small, the CO₂ is generally retained over short periods (usually months or years). Processes using captured CO₂ as feedstock instead of fossil hydrocarbons do not always achieve net lifecycle emission reductions (7.3.1, 7.3.2, 7.3.3, 7.3.4).

¹⁴ Industrial uses of CO₂ refer to those uses that do not include EOR, which is discussed in paragraph 7

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

There is relatively little experience in combining CO₂ capture, transport and storage into a fully integrated CCS system. The use of CCS for large-scale power plants (the potential application of major interest) still remains to be implemented (Section 1.4.1, 3.3.2, 3.5.2, 4.2.2).

Table S.2. Current state of technological development of CCS system components. The X's indicate the highest level of maturity for each component.

| <i>CCS component</i> | <i>CCS technology</i> | <i>Research phase</i> ¹³ | <i>Demonstration phase</i> ⁷ | <i>Economically feasible under specific conditions</i> ⁵ | <i>Mature market</i> ⁶ |
|------------------------------------|--|-------------------------------------|---|---|-----------------------------------|
| Capture | Post combustion | | | X | |
| | Pre combustion | | | X | |
| | Oxyfuel combustion | | X | | |
| | Industrial separation (natural gas processing, ammonia production) | | | | X |
| Transportation | Pipeline | | | | X |
| | Shipping | | | X | |
| Geological storage | Enhanced Oil Recovery (EOR) | | | | X ^a |
| | Gas or oil fields | | | X | |
| | Saline formations | | | X | |
| | Enhanced Coal Bed Methane recovery (ECBM) | | X | | |
| Ocean storage | Direct injection (dissolution type) | X | | | |
| | Direct injection (lake type) | X | | | |
| Mineral carbonation | Natural silicate minerals | X | | | |
| | Waste materials | | X | | |
| Industrial uses of CO ₂ | | | | | X |

^a CO₂ injection for EOR is a mature market technology, but when used for CO₂ storage, it is only "economically feasible under specific conditions".

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What is the geographical relationship between the sources and storage opportunities for CO₂?

- 12. Large point sources of CO₂ are concentrated in proximity to major industrial and urban areas. Many such sources are within 300 km of areas that potentially hold formations suitable for geological storage (see Figure S.6). Preliminary research suggests that, globally, a small proportion of large point sources is close to potential ocean storage locations.*

Currently available literature regarding the matches between large CO₂ point sources with suitable geological storage formations is limited. Detailed regional assessments may be necessary to improve information (See Figure S.6b).

Scenario studies indicate that the number of large point sources is projected to increase in the future, and that, by 2050, given expected technical limitations, around 20 - 40% of global fossil fuel CO₂ emissions could be technically suitable for capture, including 30 - 60% of electricity generation and 30 - 40% of industrial CO₂ emissions. Emissions from large-scale biomass conversion facilities could also be technically suitable for capture. The proximity of future large point sources to potential storage sites has not been studied (Sections 2.3, 2.4.3).

- 13. CCS enables the control of the CO₂ emissions from fossil fuel-based production of electricity or hydrogen, which in the longer term could reduce part of the dispersed CO₂ emissions from transport and distributed energy supply systems.*

Electricity could be used in vehicles, and hydrogen could be used in fuel cells, including in the transport sector. Gas and coal conversion with integrated CO₂ separation (without storage) is currently the dominant option for production of hydrogen. More fossil fuel or biomass-based hydrogen or electricity production would result in an increased number of large CO₂ sources that are technically suitable for capture and storage. At present, it is difficult to project the likely number, location and size of such sources (Sections 2.5.1, 2.5.1.2).

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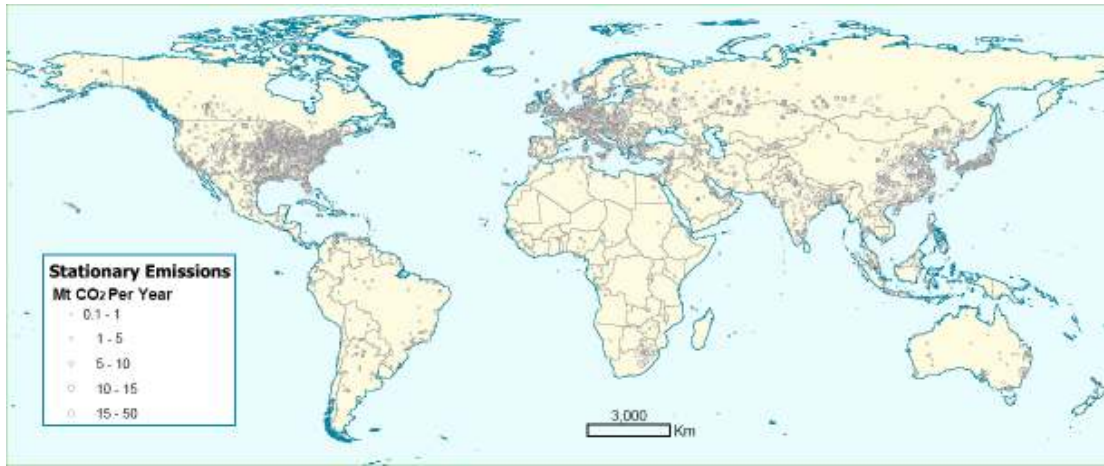


Figure S.6a. Global distribution of large stationary sources of CO₂ (Based on a compilation of publicly available information on global emission sources, IEA GHG 2002)

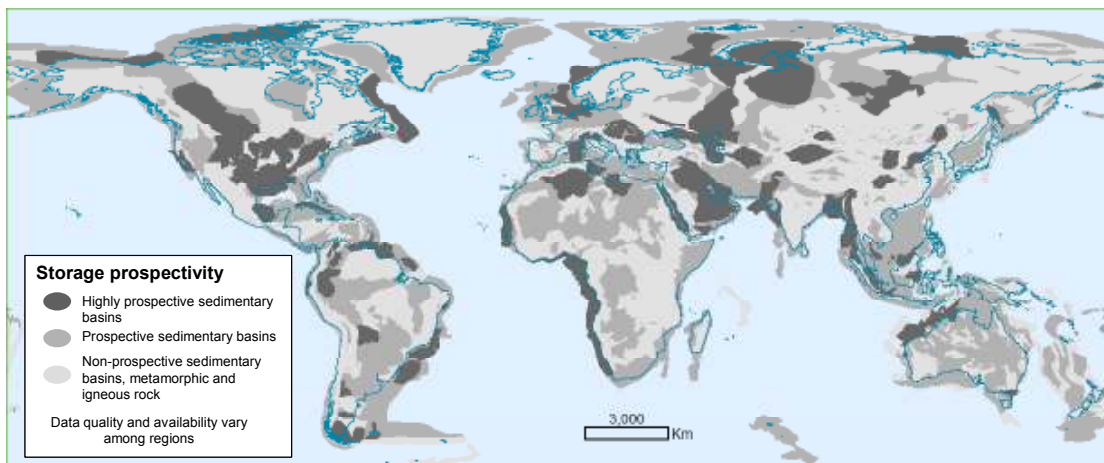


Figure S.6b. Prospective areas in sedimentary basins where suitable saline formations, oil or gas fields, or coal beds may be found. Locations for storage in coal beds are only partly included. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present in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

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What are the costs¹⁵ for CCS and what is the technical and economic potential?

14. *Application of CCS to electricity production, under 2002 conditions, is estimated to increase electricity generation costs by about 0.01 - 0.05 US dollars¹⁶ per kilowatt hour (US\$/kWh), depending on the fuel, the specific technology, the location, and the national circumstances. Including the benefits of EOR would reduce additional electricity production costs due to CCS by around 0.01 to 0.02 US\$/kWh¹⁷ (see Table S.3 for absolute electricity production costs and Table S.4 for costs in US\$/tCO₂ avoided). Increases in market prices of fuels used for power generation would generally tend to increase the cost of CCS. The quantitative impact of oil price on CCS is uncertain. However, revenue from EOR would generally be higher for higher oil prices. Whilst applying CCS to biomass-based power production at current small scale would add substantially to the electricity costs, co-firing of biomass in a larger coal-fired power plant with CCS would be more cost-effective.*

Costs vary considerably in both absolute and relative terms from country to country. Since neither Natural Gas Combined Cycle, Pulverized Coal nor Integrated Gasification Combined Cycle systems have yet been built at a full scale with CCS, the costs of these systems cannot be stated with a high degree of confidence at this time. In the future, the costs of CCS could be reduced by research and technological development, and economies of scale. Economies of scale could also bring down the cost of biomass-based CCS systems considerably over time. Applying CCS to biomass-fuelled or co-fired conversion facilities would lead to lower or negative¹⁸ CO₂ emissions, which could reduce the costs for this option, depending on the market value of CO₂ emission reductions (Sections 3.7.5.4, 8.2.4, Table 8.3).

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

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

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

¹⁸ If for example the biomass is harvested at an unsustainable rate (that is, faster than the annual re-growth), the net CO₂ emissions of the activity might not be negative.

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Table S.3. Costs of CCS: production costs of electricity for different types of generation, without capture and for the CCS system as a whole. The cost of a full CCS system for electricity generation from a newly built, large-scale fossil fuel-based power plant depends on a number of factors, including the characteristics of the power plant and the capture system, the specifics of the storage site, the amount of CO₂, and the required transport distance. The numbers assume experience with a large-scale plant. Gas prices are assumed to be 2.8 - 4.4 US\$ per gigajoule (GJ), coal prices 1 - 1.5 US\$/GJ (Based on Table 8.3 and 8.4).

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

Table S.4. CO₂ avoidance costs for the complete CCS system for electricity generation, for different combinations of reference power plants without CCS and power plants with CCS (geological and EOR)¹⁹. The amount of CO₂ avoided is the difference between emissions of the reference plant and the emissions of the power plant with CCS. Gas prices are assumed to be 2.8 - 4.4 US\$/GJ, coal prices 1 - 1.5 US\$/GJ (Based on Table 8.3a and 8.4).

| Type of power plant with CCS | Natural Gas Combined Cycle reference plant | Pulverized Coal reference plant |
|---|--|---------------------------------|
| | US\$/tCO ₂ avoided | US\$/tCO ₂ avoided |
| Power plant with capture and geological storage | | |
| Natural Gas Combined Cycle | 40 – 90 | 20 – 60 |
| Pulverized Coal | 70 – 270 | 30 – 70 |
| Integrated Gasification Combined Cycle | 40 – 220 | 20 – 70 |
| Power plant with capture and EOR ¹⁷ | | |
| Natural Gas Combined Cycle | 20 – 70 | 0 – 30 |
| Pulverized Coal | 50 – 240 | 10 – 40 |
| Integrated Gasification Combined Cycle | 20 – 190 | 0 – 40 |

¹⁹ Integrated Gasification Combined Cycle 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 Pulverized Coal plant. The incremental cost in US\$/tCO₂ avoided for an Integrated Gasification Combined Cycle plant when CCS is applied would range from 15 to 55 US\$/tCO₂ avoided with geological storage, and -5 to 30 US\$/tCO₂ avoided with EOR.

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15. *Retrofitting existing plants with CO₂ capture is expected to lead to higher costs and significantly reduced overall efficiencies than for newly built power plants with capture. The cost disadvantages of retrofitting may be reduced for some relatively new and highly efficient existing plants, or where a plant is substantially upgraded or rebuilt.*

Costs of retrofitting CCS to existing installations vary. Industrial sources of CO₂ can more easily be retrofitted with CO₂ separation, but integrated power plant systems would need more profound adjustment. In order to reduce future retrofit costs, new plant designs could take future CCS application into account (3.1.4, 3.2.3, 3.2.4).

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

Costs for the various components of a CCS system vary widely, depending on the reference plant and the wide range in CO₂ source, transport and storage situations (see Table S.5). Over the next decade the cost of capture could be reduced by 20-30% and more should be achievable by new technologies that are still in the research or demonstration phase. The costs of transport and storage of CO₂ could decrease slowly as the technology matures further and the scale increases (Sections 1.5.1.4, 3.7.13, 8.2).

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Table S.5. 2002 cost ranges for the components of a CCS system, 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\$/CO₂ avoided. All numbers are representative of costs for large-scale, new installations with natural gas prices assumed to be 2.8 - 4.4 US\$/GJ and coal prices 1 - 1.5 US\$/GJ (5.9.5, 8.2.1, 8.2.2, 8.2.3, Table 8.1 and 8.2).

| <i>CCS system components</i> | <i>Cost range</i> | <i>Remarks</i> |
|--|--|---|
| Capture from a coal- or gas-fired power plant | 15 - 75 US\$/tCO ₂ net captured | Net costs of captured CO ₂ , compared to the same plant without capture |
| Capture from hydrogen and ammonia production or gas processing | 5 - 55 US\$/tCO ₂ net captured | Applies to high-purity sources requiring simple drying and compression |
| Capture from other industrial sources | 25 - 115 US\$/tCO ₂ net captured | Range reflects use of a number of different technologies and fuels |
| Transportation | 1 - 8 US\$/tCO ₂ transported | Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) MtCO ₂ /yr. |
| Geological storage ^a | 0.5 - 8 US\$/tCO ₂ injected | Excluding potential revenues from EOR or ECBM. |
| Geological storage: monitoring and verification | 0.1 - 0.3 US\$/tCO ₂ injected | This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements |
| Ocean storage | 5 - 30 US\$/tCO ₂ injected | Including offshore transportation of 100 - 500 km, excluding monitoring and verification |
| Mineral carbonation | 50 - 100 US\$/tCO ₂ net mineralized | Range for the best case studied. Includes additional energy use for carbonation |

^a Over the long term, there may be additional costs for remediation and liabilities

17. *Energy and economic models indicate that the major CCS system's contribution to climate change mitigation would come from deployment in the electricity sector. Most modelling as assessed in this report suggests that CCS systems begin to deploy at a significant level when CO₂ prices begin to reach approximately 25 - 30 US\$/tCO₂.*

Low-cost capture possibilities (in gas processing, and hydrogen and ammonia manufacture, where separation of CO₂ is already done) in combination with short (< 50 km) transport distances and storage options that generate revenues (such as EOR) can lead to limited storage of CO₂ (up to 360 MtCO₂/yr) under circumstances of low or absent incentives (Sections 2.2.1.3, 2.3.2, 2.4, 8.3.3)

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18. *Available evidence suggests that worldwide, it is likely²⁰ that there is a technical potential²¹ of at least about 2,000 GtCO₂ (545 GtC) of storage capacity in geological formations²².*

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

Model calculations for the capacity to store CO₂ in the oceans indicate that this could be on the order of thousands of GtCO₂, depending on the assumed stabilization level in the atmosphere²³, and on environmental constraints such as ocean pH change. The extent to which mineral carbonation may be used can currently not be determined, since it depends on the unknown amount of silicate reserves that can be technically exploited, and environmental issues such as the volume of product disposal (Sections 5.3, 6.3, 7.2.3, Table 5.2).

19. *In most scenarios for stabilization of atmospheric greenhouse gas concentrations between 450 and 750 ppmv CO₂ and in a least-cost portfolio of mitigation options, the economic potential²⁴ of CCS would amount to 220 - 2,200 GtCO₂ (60 - 600 GtC) cumulatively, which would mean that CCS contributes 15 to 55% to the cumulative mitigation effort worldwide until 2100, averaged over a range of baseline scenarios. It is likely²⁰ that the technical potential²¹ for geological storage is sufficient to cover the high end of the economic potential range, but for specific regions, this may not be true.*

Uncertainties in these economic potential estimates are significant. For CCS to achieve such an economic potential, several hundreds to thousands of CO₂ capture systems would need to be installed over the coming century, each capturing some 1 - 5 MtCO₂ per year. The actual use of CCS, as for other mitigation options, is likely to be lower than the economic potential due to factors such as environmental impacts, risks of leakage, and the lack of a clear legal framework or public acceptance (Sections 1.4.4, 8.3.1, 8.3.3, 8.3.3.4).

20. *In most scenario studies, the role of CCS in mitigation portfolios increases over the course of the century and including CCS in a mitigation portfolio is found to reduce the costs of stabilizing CO₂ concentrations by 30% or more.*

²⁰ "Likely" is a probability between 66 and 90%.

²¹ "Technical potential" as defined in the TAR is the amount by which it is possible to reduce greenhouse gas emissions by implementing a technology or practice that already has been demonstrated.

²² This statement is based on expert judgment of the authors, based on available literature. It reflects the uncertainty about the storage capacity estimates (Section 5.3.7).

²³ This approach takes into account that the CO₂ injected in the ocean will after some time reach equilibrium with the atmosphere.

²⁴ Economic potential is the amount of greenhouse gas emissions reductions from a specific option that could be achieved cost-effectively, given prevailing circumstances (i.e. a market value of CO₂ reductions and costs of other options).

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

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

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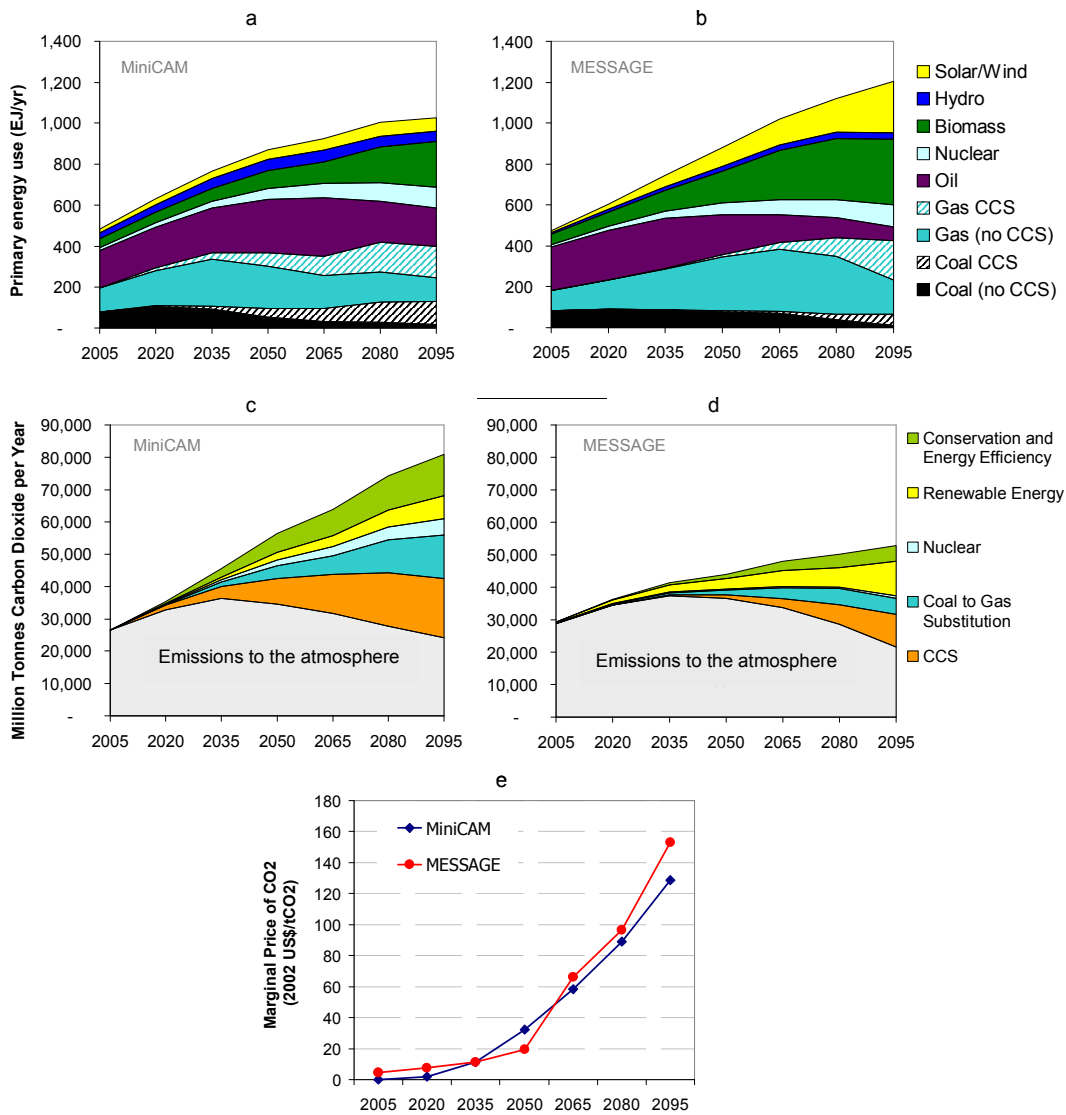


Figure S.7. These figures are an illustrative example of the global potential contribution of CCS as part of a mitigation portfolio. They are based on two alternative integrated assessment models (MESSAGE and MiniCAM) adopting the same assumptions for the main emissions drivers. The results would vary 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 CO₂ emissions in grey and corresponding contributions of main emissions reduction measures in colour. Panel e) shows the calculated marginal price of CO₂ reductions (8.3.3, Box 8.3).

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

21. *The local risks²⁵ associated with CO₂ pipeline transport could be similar to or lower than those posed by hydrocarbon pipelines in operation.*

For existing CO₂ pipelines, mostly in areas of low population density, accident numbers reported per kilometre pipeline are very low and are comparable to those for hydrocarbon pipelines. A sudden and large release of CO₂ would pose immediate dangers to human life and health, if there were exposure to concentrations of CO₂ greater than 7 - 10% by volume in air. Pipeline transport of CO₂ through populated areas requires attention to route selection, overpressure protection, leak detection and other design factors. No major obstacles to pipeline design for CCS are foreseen (Sections 4.5.2, AI.3.2).

22. *With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO₂ releases if they arise, the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas.*

Natural CO₂ reservoirs contribute to the understanding of the behaviour of CO₂ underground. Features of storage sites with a low probability of leakage include highly impermeable caprocks, geological stability, absence of leakage paths and effective trapping mechanisms. There are two different types of leakage scenarios: 1) Abrupt leakage, through injection well failure or leakage up an abandoned well, and 2) gradual leakage, through undetected faults, fractures, or wells. Impacts of elevated CO₂ concentrations in the shallow subsurface could include lethal effects on plants and subsoil animals, and contamination of groundwater. High fluxes in conjunction with stable atmospheric conditions could lead to local high CO₂ concentrations in the air that could harm animals or people. Pressure build-up caused by CO₂ injection could trigger small seismic events.

While there is limited experience with geological storage, closely related industrial experience and scientific knowledge could serve as a basis for appropriate risk management, including remediation. The effectiveness of the available risk management methods still needs to be demonstrated for use with CO₂ storage. If there is leakage at a storage site, remediation to stop the leakage could involve standard well repair techniques, or interception and extraction of the CO₂ before it would leak into a shallow groundwater aquifer. Given the long timeframes associated with geological storage of CO₂, site monitoring may be required for very long periods (Sections 5.6, 5.7, Table 5.4 and 5.7, Figure 5.25).

²⁵ In discussing the risks, we assume that risk is the product of the probability that an event will occur and the consequences of the event if it does occur.

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23. *Adding CO₂ to the ocean or forming pools of liquid CO₂ on the ocean floor at industrial scales will alter the local chemical environment. Experiments have shown that sustained high concentrations of CO₂ would cause mortality of ocean organisms. CO₂ effects on marine organisms will have ecosystem consequences. The chronic effects of direct CO₂ injection into the ocean on ecosystems over large ocean areas and long time scales have not yet been studied.*

Model simulations, assuming a release from seven locations at 3,000 m depth, where ocean storage provides 10% of the mitigation effort for stabilization at 550 ppmv CO₂, resulted in acidity increases (pH decrease >0.4) over approximately 1% of the ocean volume. For comparison: in such a stabilization case without ocean storage a pH decrease >0.25 relative to pre-industrial levels at the entire ocean surface can be expected. A 0.2 to 0.4 pH decrease is significantly greater than pre-industrial variations in average ocean acidity. At these levels of pH change, some effects have been found in organisms that live near the ocean's surface, but chronic effects have not yet been studied. A better understanding of these impacts is required before a comprehensive risk assessment can be accomplished. There is no known mechanism for sudden or catastrophic release of stored CO₂ from the ocean to the atmosphere. Gradual release is discussed in SPM paragraph 26. Conversion of molecular CO₂ to bicarbonates or hydrates before or during CO₂ release would reduce the pH effects and enhance the retention of CO₂ in the ocean, but this would increase the costs and other environmental impacts (Sections 6.7.4, 6.7).

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

Industrial fixation of one tonne of CO₂ requires between 1.6 and 3.7 tonnes of silicate rock. The impacts of mineral carbonation are similar to those of large-scale surface mines. They include land-clearing, decreased local air quality and affected water and vegetation as a result of drilling, moving of earth and grading and leaching of metals from mining residues, which indirectly also may result in habitat degradation. Most products of mineral carbonation need to be disposed of, which would require landfills and additional transport (Sections 7.2.4.5, 7.2.6).

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Will physical leakage of stored CO₂ compromise CCS as a climate change mitigation option?

25. *Observations from engineered and natural analogues as well as models suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely²⁶ to exceed 99% over 100 years, and is likely²⁰ to exceed 99% over 1,000 years.*

For well-selected, designed and managed geological storage sites, the vast majority of the CO₂ will gradually be immobilized by various trapping mechanisms and, in that case, could be retained for up to millions of years. Because of these mechanisms, storage could become more secure over longer timeframes (Sections 1.6.4, 5.2.2, 5.7.3, Box 5.4, Table 5.5, 6.2).

26. *Release of CO₂ from ocean storage would be gradual over hundreds of years.*

Ocean tracer data and model calculations indicate that, in case of ocean storage, depending on the depth of injection and the location, the fraction retained is 65 to 100% after 100 years, and 30 - 85% after 500 years (lower percentage for injection at 1,000 m depth, higher percentage at 3,000 m) (Sections 1.6.4, 6.3, 6.2, 7.2.8)

27. *In the case of mineral carbonation, the CO₂ stored would not be released to the atmosphere (Section 7.2.8).*

28. *If continuous leakage of CO₂ occurs it could, at least in part, offset the benefits of CCS for mitigating climate change. Assessments of the implications of leakage for climate change mitigation depend on the framework chosen for decision-making and on the information on the fractions retained for geological or ocean storage as presented in paragraphs 25 and 26.*

Studies conducted to address the question of how to deal with non-permanent storage are based on different approaches: the value of delaying emissions, cost minimization of a specified mitigation scenario, or allowable future emissions in the context of an assumed stabilization of atmospheric greenhouse gas concentrations. Some of these studies allow future leakage to be compensated by additional reductions in emissions; the results depend on assumptions regarding the future cost of reductions, discount rates, the amount of CO₂ stored, and the atmospheric concentration stabilization level assumed. In other studies, compensation is not seen as an option because of political and institutional uncertainties and the analysis focuses on limitations set by the assumed stabilization level and the amount stored. While specific results of the range of studies vary with the methods and assumptions made, all studies imply that, if

²⁶ "Very likely" is a probability between 90 and 99%.

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CCS is to be acceptable as a mitigation measure, there must be an upper limit to the amount of leakage that can take place (Sections 1.6.4, 8.4).

What are the legal and regulatory issues for implementing CO₂ storage?

29. *Some regulations for operations in the subsurface exist that may be relevant or in some cases directly applicable to geological storage, but few countries have specifically developed legal or regulatory frameworks for long-term CO₂ storage.*

Existing laws and regulations regarding inter alia mining, oil and gas operations, pollution control, waste disposal, drinking water, treatment of high-pressure gases, and subsurface property rights may be relevant to geological CO₂ storage. Long-term liability issues associated with the leakage of CO₂ to the atmosphere and local environmental impacts are generally unresolved. Some States take on long-term responsibility in situations comparable to CO₂ storage, such as underground mining operations (Sections 5.8.2, 5.8.3).

30. *No formal interpretations so far have been agreed regarding whether or under what conditions CO₂ injection into the geological sub-seabed or the ocean is compatible with certain provisions of international law.*

Currently, there are several treaties (notably the London²⁷ and OSPAR²⁸ Conventions) that potentially apply to the injection of CO₂ into the geological sub-seabed or the ocean. All these treaties have been drafted without specific consideration of CO₂ storage (Sections 5.8.1, 6.8.1).

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

31. *The current IPCC Guidelines²⁹ do not include methods specific to estimating emissions associated with CCS.*

The general guidance provided by the IPCC can be applied to CCS. A few countries currently do so, in combination with their national methods for estimating emissions. The IPCC guidelines themselves do not yet provide specific methods for estimating emissions associated with CCS. These are expected to be

²⁷ 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.

²⁸ 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.

²⁹ Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, and Good Practice Guidance Reports; Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, and Good Practice Guidance for Land Use, Land-Use Change and Forestry

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provided in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Specific methods may be required for net capture and storage of CO₂, physical leakage, fugitive emissions and negative emissions associated with biomass applications of CCS systems. (Sections 9.2.1, 9.2.2).

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

Several techniques are available or under development for monitoring and verification of CO₂ emissions from CCS, but they vary in applicability, site specificity, detection limits, and uncertainties (9.2.3, 5.6.1, 6.6.2).

33. *CO₂ might be captured in one country and stored in another with different commitments. Issues associated with accounting for cross-border storage are not unique to CCS.*

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

What are the gaps in knowledge?

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