

SUMMARY OF THE IPCC SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE

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Introduction

Carbon dioxide capture and storage (CCS) is an option for reducing atmospheric emissions of CO₂ from human activities. CCS involves the use of technology to first collect and concentrate the CO₂ produced at 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. The IPCC Special Report¹ assesses the current state of knowledge regarding the technical, scientific, environmental, economic and societal dimensions of CCS. It also assesses CCS in the context of a portfolio of potential climate change mitigation measures. The summary below draws upon the Technical Summary and text of the full report to highlight the major issues addressed.

Sources of CO₂

Globally, emissions of CO₂ from fossil-fuel use in the year 2000 totaled about 23.5 GtCO₂/yr. Of this, close to 60% was attributed to large (>0.1 MtCO₂/yr) stationary emission sources, not all of which are amenable to CO₂ capture. The greatest source of emissions is fossil-fuel power plants. Although large sources are distributed throughout the world, the database reveals four major clusters of emissions in North America (midwest and eastern US), 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 evenly distributed globally.

The distance from an emission source to a potential storage site can have a significant bearing on whether or not CCS can play a significant role in reducing CO₂ emissions. In broad terms, there is potentially good correlation between major sources of CO₂ and prospective sedimentary basins, with many sources lying either directly above, or less than 300 km from areas with potential for geological storage. However, more detailed geological analysis on a regional level is required to confirm the suitability of potential storage sites.

Capture of CO₂

CO₂ is routinely separated today at large industrial plants such as natural gas processing and ammonia production facilities in order to meet process demands (without concern for storage). CO₂ capture also has been applied to several small power plants. However, to date there have been no applications of CCS at large-scale power plants (on the scale of hundreds of megawatts) that are the major sources of current and projected CO₂ emissions.

Current commercial CO₂ capture systems can reduce power plant CO₂ emissions per kilowatt-hour (kWh) by 85-90%. The energy required to operate CO₂ capture systems (including energy for CO₂ compression needed to transport and store CO₂) significantly reduces the overall efficiency of power generation, leading to increased fuel requirements, solid wastes and other environmental impacts relative to the same type of plant without capture.

For new power plants, recent studies indicate that CO₂ capture adds 12-36 US\$/MWh (1.2-3.6 cents/kWh) to the cost of electricity production (COE) relative to a similar plant without capture (based on 2002 US\$). This represents an increase of 40-85% for a new supercritical pulverized coal (PC) plant, 35-70% for a natural gas combined cycle (NGCC) plant, and 20-55% for an integrated gasification combined cycle (IGCC) plant using bituminous coal. The cost per net tonne of CO₂ captured ranges from 13-74 US\$/t CO₂, depending on plant type, size, fuel type, and a host of other factors. These costs include CO₂ compression but not additional transport and storage costs. NGCC systems typically have a lower overall COE than new PC and IGCC plants (with or without capture) for large base load plants with high capacity factors (75% or more), and with gas prices below about 4 US\$/GJ. Most studies indicate that IGCC plants are slightly more costly without capture and less costly with capture than similarly sized PC plants. However, differences in cost for plants with CO₂ capture can vary with coal type and other local factors. The lowest CO₂ capture costs (averaging about 15 US\$/net tonne CO₂ captured) were found for industrial processes such as hydrogen production plants that produce concentrated CO₂ streams as part of the current production process. Such industrial processes may represent some of the earliest opportunities for CCS. In all cases, CO₂ capture costs are highly dependent upon technical, economic and financial factors related to the design and operation of the production process or power system of interest, as well as the design and operation of the CO₂ capture technology employed. Comparisons of alternative technologies, or the use of CCS cost estimates, thus require a specific context to be meaningful.

New or improved methods of CO₂ capture, combined with advanced power systems and industrial process designs, can significantly reduce CO₂ capture costs and associated energy requirements. While there is considerable uncertainty about the magnitude and timing of future cost reductions, the literature suggests that improvements to commercial technologies can reduce CO₂ capture costs by at least 20-30% over roughly the next decade, while new technologies under development promise larger cost reductions in the future. Achievement of future cost reductions, however, will require deployment and adoption of commercial technologies in the marketplace as well as sustained R&D.

Transport of CO₂

Transport is the stage of CCS that links sources and storage sites. Long-distance pipeline transport of carbon dioxide is part of current practice: such pipelines now extend over more than 2500 km in the western US, where they carry 50 MtCO₂/yr from natural CO₂ sources to enhanced oil recovery (EOR) projects in west Texas and elsewhere. The CO₂ stream should preferably be dry and free of hydrogen sulfide so that corrosion is minimal, although it is possible to design a corrosion-resistant pipeline that operates safely with a gas containing water, hydrogen sulfide and other contaminants. Typical costs range from about 1-8 US\$/t CO₂, depending on distance and other site-specific conditions.

Transport by both pipelines and shipping is covered by regulatory frameworks concerned with public safety. Pipeline transport of CO₂ through populated areas requires that attention be paid to design factors, to overpressure protection, and to leak detection. However, there is no indication that such problems for CO₂ pipelines are any more challenging than those for hydrocarbon pipelines that are widely deployed in similar areas, or that they cannot be resolved.

Carbon dioxide also is transported by marine tankers similar to those widely used for liquefied natural gas (LNG) and petroleum gases, but on a much smaller scale because of limited demand. The technology could be scaled up to large CO₂ carriers should future demands arise. Liquefied CO₂ also can be carried by rail tank and road tankers, but it appears unlikely that these modes of transport will be attractive options for large-scale CCS projects.

Geological storage of CO₂

Underground accumulation of CO₂ is a widespread geological phenomenon, with natural trapping of CO₂ in underground reservoirs. Information and experience gained from the injection and/or storage of CO₂ from a large number of existing EOR projects, as well as from three large-scale storage projects (Sleipner, Weyburn and In Salah), indicate that it is feasible to store CO₂ in geological formations as a CO₂ abatement option. Industrial analogs, including underground natural gas storage and acid gas injection projects around the world, provide additional indications that CO₂ can be safely injected and stored at well-characterized and properly managed sites. While there are differences between natural accumulations and engineered storage, it is considered likely that 99% or more of the CO₂ injected into deep geological formations at carefully selected sites will be retained for 1000 years.

Depleted oil and gas reservoirs, possibly coal formations, and particularly saline formations (deep underground porous reservoir rocks saturated with brackish water or brine), can be used for storage of CO₂. At depths below about 800–1000 m, supercritical CO₂ has a liquid-like density that provides the potential for efficient utilization of underground storage space in the pores of sedimentary rocks. CO₂ can remain trapped underground by virtue of a number of mechanisms, such as trapping below an impermeable confining layer (caprock); retention as an immobile phase trapped in the pore spaces of the storage formation; dissolution in the *in situ* formation fluids; and/or adsorption onto organic matter in coal and shale. CO₂ also may be trapped by reactions with minerals or caprock that produce carbonate minerals. Thus, CO₂ becomes less mobile over time as a result of multiple trapping mechanisms.

Despite uncertainties, the global capacity to store CO₂ deep underground is large. Depleted oil and gas reservoirs are estimated to have a storage capacity of 675–900 GtCO₂. Deep saline formations are very likely to have a storage capacity of 1000 GtCO₂. Some studies suggest it may be an order of magnitude greater than this, but quantification of the upper range is difficult until additional studies are undertaken. Capacity of unminable coal formations is uncertain, with estimates ranging from as little as 3 GtCO₂ up to 200 GtCO₂. Potential storage sites are likely to be broadly distributed in many of the world's sedimentary basins, located in the same region as many of the world's emission sources, and are likely to be adequate to store a significant proportion of those emissions well into the future.

The cost of geological storage of CO₂ is highly site-specific and dependent on factors such as the depth of the storage formation, the number of wells needed for injection, and whether the project is onshore or offshore. Current estimates of storage cost, including monitoring, generally lie in the range of 0.6–8.3 US\$/tCO₂ stored. EOR storage could lead to negative costs of 10–16 US\$/tCO₂ for oil prices of 15–20 US\$ per barrel, and more for higher oil prices.

Potential risks to humans and ecosystems from geological storage may arise from leaking injection wells, abandoned wells, leakage across faults, and ineffective confining layers. Leakage of CO₂ could potentially degrade the quality of groundwater, damage some hydrocarbon or mineral resources and have lethal effects on plants and sub-soil animals. Release of CO₂ into the atmosphere also could create local health and safety concerns. Avoiding or mitigating such impacts will require careful site selection, effective regulatory oversight, an appropriate monitoring program, and implementation of remediation methods to stop or control any CO₂ releases. Methods to accomplish these are being developed and tested.

There are few, if any, national regulations specifically dealing with CO₂ storage, but regulations dealing with oil and gas, groundwater, and the underground injection of fluids can in many cases be readily adapted and/or adopted. However, there are no regulations relating specifically to long-term responsibility for storage. A number of international laws that predate consideration of CO₂ storage are relevant to offshore geological storage. Consideration of whether these laws do or do not permit offshore geological storage is under way.

Ocean storage of CO₂

Another potential CO₂ storage option is to transport CO₂ via pipelines or ships to an ocean storage site, where it is injected directly into the deep ocean at depths greater than 1,000 m. As a CO₂ abatement option, ocean storage is still in the research phase. However, there have been small-scale field experiments and 25 years of theoretical, laboratory and modeling studies.

There is no practical physical limit to the amount of anthropogenic CO₂ that could be stored in the ocean. However, on a millennial time scale, the amount stored will depend on the oceanic equilibration with the atmosphere. For example, stabilizing the atmospheric CO₂ concentration at 350 to 1000 ppmv implies that 2,000 to 12,000 GtCO₂ would eventually reside in the ocean in the absence of intentional CO₂ injection. This range thus represents the upper limit for storage capacity through active injection. The storage capacity also would be affected by environmental factors or constraints, such as a maximum allowable pH change. Ocean observations and models indicate that injected CO₂ will be isolated from the atmosphere for at least several centuries, and that the fraction retained tends to be higher with deeper injection.

The injection of a few GtCO₂ would produce a measurable change in ocean chemistry in the region of injection, whereas the injection of hundreds of GtCO₂ would produce larger changes in the region of injection and eventually produce measurable changes over the entire ocean volume. Over centuries, ocean mixing will result in the loss of isolation of injected CO₂. As more CO₂ reaches the ocean surface, 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 CO₂ from the ocean into the atmosphere.

Experiments show that adding CO₂ can harm marine organisms. Effects of elevated CO₂ levels have been studied mostly 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 CO₂. Immediate mortality is expected close to injection points or CO₂ lakes on the ocean floor. The chronic effects of direct CO₂ injection on ocean organisms or ecosystems over large ocean areas and long time scales have not yet been studied. However, it is expected that ecosystem consequences will increase with increasing CO₂ concentrations and decreasing pH, although the nature of such consequences is not currently understood, nor have environmental criteria yet been identified to avoid adverse effects. At present, it is also unclear how or whether species and ecosystems would adapt to sustained chemical changes.

Global and regional treaties on the law of the sea and marine environment, such as the OSPAR and the London Conventions, also affect ocean storage. Both conventions distinguish between the storage method employed and the purpose of storage to determine the legal status. As yet, however, no decision has been made about the legal status of intentional ocean storage of CO₂.

Mineral carbonation and industrial uses of CO₂

Mineral carbonation is a naturally occurring process in which CO₂ reacts with mineral elements such as calcium or magnesium to form stable compounds like calcium carbonate. In nature, this process occurs very slowly; it must therefore be accelerated considerably to be a viable storage method for anthropogenic CO₂. Research thus focuses on finding process routes that can achieve high reaction rates and reduce process energy requirements. Processes using natural silicates are in the research phase but others using industrial wastes are being demonstrated.

A commercial process would require mining, crushing and milling of mineral-bearing ores and their transport to a processing plant receiving a concentrated CO₂ stream from a capture plant. Current studies indicate that the carbonation process energy required would be 30% to 50% of the capture plant output. Considering the additional energy requirements for CO₂ capture, a CCS system with mineral carbonation would require 60% to 180% more energy input per kilowatt-hour than a reference electricity plant without capture. These large energy requirements raise the mineralization process cost significantly. The best process studied to date costs approximately 50–100 US\$/tCO₂ net mineralized. The process would require 1.6 to 3.7 tonnes of silicates to be mined per tonne of CO₂, and would produce 2.6 to 4.7 tonnes of materials to be disposed of per tonne of CO₂ stored. This would be a large operation, with environmental impacts similar to current large-scale surface mines. A number of issues still need to be clarified before estimates of maximum storage potential for mineral carbonation can be given.

Industrial uses of CO₂ can, in principle, also contribute to keeping CO₂ out of the atmosphere by storing it in the stock of carbon-bearing manufactured products. However, most of the CO₂ currently used by industrial processes has storage times of only days to months before the stored carbon is degraded to CO₂ and emitted to the atmosphere. Such short time scales do not contribute meaningfully to climate change mitigation. In addition, the total current industrial use of about 120 MtCO₂/yr worldwide is small compared to emissions from major anthropogenic sources. While some industrial processes store a small amount of CO₂ (roughly 20 MtCO₂/yr) for

up to several decades, the total amount of long-term (century-scale) storage is presently on the order of only 1 MtCO₂/yr or less, with no prospects for major increases.

Costs and economic potential of CCS

The literature reports a fairly wide range of costs for CCS systems employed at fossil-fuel power plants and various industrial processes. The range is driven primarily by site-specific factors such as the technical characteristics of the power plant or industrial facility, the characteristics of the storage site, and the required transport distance. Measured in constant 2002 US\$, the application of CO₂ capture technology would add about 1.8 to 3.4 US cents/kWh to the levelized cost of electricity production from a new pulverized coal power plant, 0.9 to 2.2 US cents/kWh to the COE from an integrated gasification combined cycle (IGCC) coal power plant, and 1.2 to 2.4 US cents/kWh for a natural gas combined-cycle (NGCC) power plant. Additional costs for CO₂ transport and geological storage typically range from 0.05–0.6 US cents/kWh for coal-based plants and slightly less for NGCC plants. Compared to similar plants without CCS, the cost of CO₂ avoided for capture plants using geological storage range from 30–71 US\$/tCO₂ avoided for supercritical PC plants, 38–91 US\$/tCO₂ for NGCC plants, and 14–53US\$/tCO₂ for IGCC plants. If available, geological storage via EOR can further reduce these mitigation costs.

CCS technologies also can be applied to other industrial processes such as hydrogen production. In some applications, the cost of capture is lower than for fossil-fired power plants, but costs vary widely. CCS also can be applied to biomass-fed energy systems, where credits for CO₂ stored in the biomass can potentially yield negative net emissions and reduce the net cost of CO₂ avoided.

Energy and economic models used to study future scenarios indicate that CCS systems are unlikely to be deployed on a large scale in the absence of policies that substantially limit greenhouse gas emissions to the atmosphere. Deployment of CCS systems starts to be significant when the effective carbon price reaches approximately 25–30 US\$/tCO₂. While models differ in the projected mix of technologies needed to stabilize atmospheric CO₂ concentrations, the consensus is that CCS could be an important component of a broad portfolio of measures to reduce emissions. Furthermore, inclusion of CCS in the portfolio can reduce overall costs. In the majority of scenarios for atmospheric stabilization at 450–750 ppmv CO₂, the use of CCS results in 220–2200 GtCO₂ stored by the end of this century. This is within the global estimates of total CO₂ storage capacity noted earlier. The actual use of CCS is likely to be lower than the model estimates due to technology development barriers that are not adequately accounted for in current modeling frameworks.

Given the potential for hundreds to thousands of gigatonnes of CO₂ to be stored in various geological formations and the ocean, questions have been raised about the implications of gradual leakage from these reservoirs. While the results of several studies vary with the methods and assumptions employed, the outcomes suggest that some CO₂ leakage can be accommodated while progressing towards the goal of stabilizing atmospheric concentrations of CO₂. At the same time, all studies imply that if CCS is to be acceptable as a mitigation measure, there must be an upper limit on the amount of leakage that can take place.

Emission inventories and accounting

Another important aspect of CO₂ capture and storage is the development and application of methods to estimate and report the quantities of CO₂ emissions that are reduced, avoided, or removed from the atmosphere by CCS. Two issues are involved: the estimation and reporting of emissions for national greenhouse gas inventories, and accounting for CCS under international agreements to limit emissions.

With regard to national inventories, current IPCC guidelines do not specifically include CCS options. However, these guidelines are undergoing revisions during 2006 that should provide some guidance. With regards to international commitments, the rules and methods for accounting for CCS may be different than those used in traditional emissions inventories because CCS has the potential to move CO₂ across traditional accounting boundaries (e.g., CO₂ might be captured in one country and stored in another, or captured in one year and partly released from storage in a later year). To date, most of the scientific, technical and political discussions on accounting for stored CO₂ have focused on sequestration in the terrestrial biosphere. However, the history of these negotiations may provide some guidance for the development of accounting methods for CCS. Guidelines for monitoring greenhouse gas emissions associated with CCS also will be needed.

Gaps in knowledge

In all of the areas discussed above, as well as in the larger domain of policy considerations related to climate change mitigation, additional analysis, knowledge and experience can facilitate future decision-making about the large-scale deployment of CCS. Elaboration of key knowledge gaps in each of the major areas can be found in the Technical Summary and full text of the Special Report.

References

¹*Special Report on Carbon Dioxide Capture and Storage*, Metz, B., et.al (eds.), Intergovernmental Panel on Climate Change, Cambridge University Press, 2005. Also available at: <http://www.ipcc.ch>