Implementing Geological Carbon Capture and Storage: Assessing the Challenges

Intergovernmental Panel on Climate Change

Introduction

Scientists have come to a consensus that climate change is occurring and that the anthropogenic emissions of greenhouse gases (GHG) are a significant contributor. It is therefore essential that countries around the world find a way to manage these emissions. Carbon dioxide (CO_2) is the largest anthropogenic GHG and coal burning power plants are a leading emitter.

Carbon capture and storage (CCS) technologies may be an option for capturing CO_2 before it enters the atmosphere and sequestering the gas terrestrially. The U.S. and governments around the world are evaluating the allocation of financial resources for this and other mitigation options. This article highlights some of the major challenges associated with CCS, including site selection, transportation, monitoring, risk management, liability, financial requirements and knowledge gaps.

Although the IPCC report assesses the potential for ocean storage of CO_2, most current projects, proposals and research focuses on underground geological storage. It is the subject of this article.

The IPCC report indicates that due to high costs, CCS systems are unlikely to be deployed on a large scale in the absence of explicit government policies that require substantial reduction of greenhouse gas emissions to the atmosphere. Ed.

This article is a series of excerpts from the Intergovernmental Panel on Climate Change (IPCC), Special Report on Carbon Dioxide Capture and Storage, 2005. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

Underground Geological Storage

Capture and geological storage of CO_2 provides a way to avoid emitting CO_2 into the atmosphere, by capturing CO_2 from major stationary sources, transporting it usually by pipeline and injecting it into suitable deep rock formations.

Geological storage of CO_2 has been a natural process in the Earth's upper crust for hundreds of millions of years. Storage of anthropogenic CO_2 as a greenhouse gas mitigation option was first proposed in the 1970s, but little research was done until the early 1990s.

If CO_2 storage is to be undertaken on the scale necessary to make deep cuts to atmospheric CO_2 emissions, there must be hundreds, and perhaps even thousands, of large-scale geological storage projects under way worldwide.

CO_2 Storage Mechanisms in Geological Formations

The effectiveness of geological storage depends on a combination of physical and geochemical trapping mechanisms. The most effective storage sites are those where CO_2 is immobile because it is trapped permanently under a thick, low-permeability seal or is converted to solid minerals or is adsorbed on the surfaces of coal micropores or through a combination of physical and chemical trapping mechanisms. Not all sedimentary basins are suitable for CO_2 storage; some are too shallow and others are dominated by rocks with low permeability or poor confining characteristics.

General Site-Selection Criteria

There are many sedimentary regions in the world variously suited for CO_2 storage. In general, geological storage sites should have (1) adequate capacity and injectivity, (2) a satisfactory sealing caprock or confining unit and (3) a sufficiently stable geological environment to avoid compromising the integrity of the storage site. Criteria for assessing basin suitability (Bachu, 2000, 2003; Bradshaw *et al*., 2002) include: basin characteristics (tectonic activity, sediment type, geothermal and hydrodynamic regimes); basin resources (hydrocarbons, coal, salt), industry maturity and infrastructure; and societal issues such as level of development, economy, environmental concerns, public education and attitudes.

Depleted oil and gas reservoirs are prime candidates for CO_2 storage for several reasons. Enhanced oil recovery (EOR) through CO_2 flooding (by injection) offers potential economic gain from incremental oil production.

Security and Duration of CO_2 Storage in Geological Formations

Evidence from oil and gas fields indicates that hydrocarbons and other gases and fluids including CO_2 can remain trapped for millions of years (Magoon and Dow, 1994; Bradshaw *et al*., 2005). However, some natural traps do leak, which reinforces the need for careful site selection, characterization and injection practices. For example, seepage of CO_2 into Lake Nyos (Cameroon) resulted in CO_2 saturation of water deep in the lake, which in 1987 produced a very large-scale and (for more than 1,700 persons) ultimately fatal release of CO_2 when the lake overturned (Kling *et al*., 1987). Natural storage and events such as Lake Nyos are not representative of geological storage for predicting seepage from engineered sites, but can be useful for studying the health, safety and environmental effects of CO_2 leakage.

Matching of CO_2 Sources and Geological Storage Sites

Matching of CO_2 sources with geological storage sites requires detailed assessment of source quality and quantity, transport and economic and environmental factors. If the storage site is far from CO_2 sources or is associated with a high level of technical uncertainty, then its storage potential may never be realized.

The following factors should be considered when selecting CO_2 storage sites and matching them with CO_2 sources (Winter and Bergman, 1993; Bergman *et al*., 1997; Kovscek, 2002): volume, purity and rate of the CO_2 stream; suitability of the storage sites, including the seal; proximity of the source and storage sites; infrastructure for the capture and delivery of CO_2; existence of a large number of storage sites to allow diversification; known or undiscovered energy, mineral or groundwater resources that might be compromised; existing wells and infrastructure; viability and safety of the storage site; injection strategies and, in the case of EOR and enhanced coal bed methane (ECBM) projects, production strategies, which together affect the number of wells and their spacing; terrain and right of way; location of population centers; local expertise; and overall costs and economics.

Although technical suitability criteria are initial indicators for identifying potential CO_2 storage sites, once the best candidates have been selected, further considerations will be controlled by economic, safety and environmental aspects. These criteria must be assessed for

Types of Data That Are Used to Characterize and Select Geological CO_2 Storage Sites

Seismic profiles across the area of interest, preferably three- dimensional or closely spaced two-dimensional surveys;

- Structure contour maps of reservoirs, seals and aquifers;
- Detailed maps of the structural boundaries of the trap where the CO_2 will accumulate, especially highlighting potential spill points;
- Maps of the predicted pathway along which the CO_2 will migrate from the point of injection;
- Documentation and maps of faults and fault;
- Facies maps showing any lateral facies changes in the reservoirs or seals;
- Core and drill cuttings samples from the reservoir and seal intervals;
- Well logs, preferably a consistent suite, including geological, geophysical and engineering logs;
- Fluid analyses and tests from downhole sampling and production testing;
- Oil and gas production data (if a hydrocarbon field);
- Pressure transient tests for measuring reservoir and seal permeability;
- Petrophysical measurements, including porosity, permeability, mineralogy (petrography), seal capacity, pressure, temperature, salinity and laboratory rock strength testing;
- Pressure, temperature, water salinity;
- *In situ* stress analysis to determine potential for fault reactivation and fault slip tendency and thus identify the maximum sustainable pore fluid pressure during injection in regard to the reservoir, seal and faults;
- Hydrodynamic analysis to identify the magnitude and direction of water flow, hydraulic interconnectivity of formations and pressure decrease associated with hydrocarbon production;
- Seismological data, geomorphological data and tectonic investigations to indicate neotectonic activity.

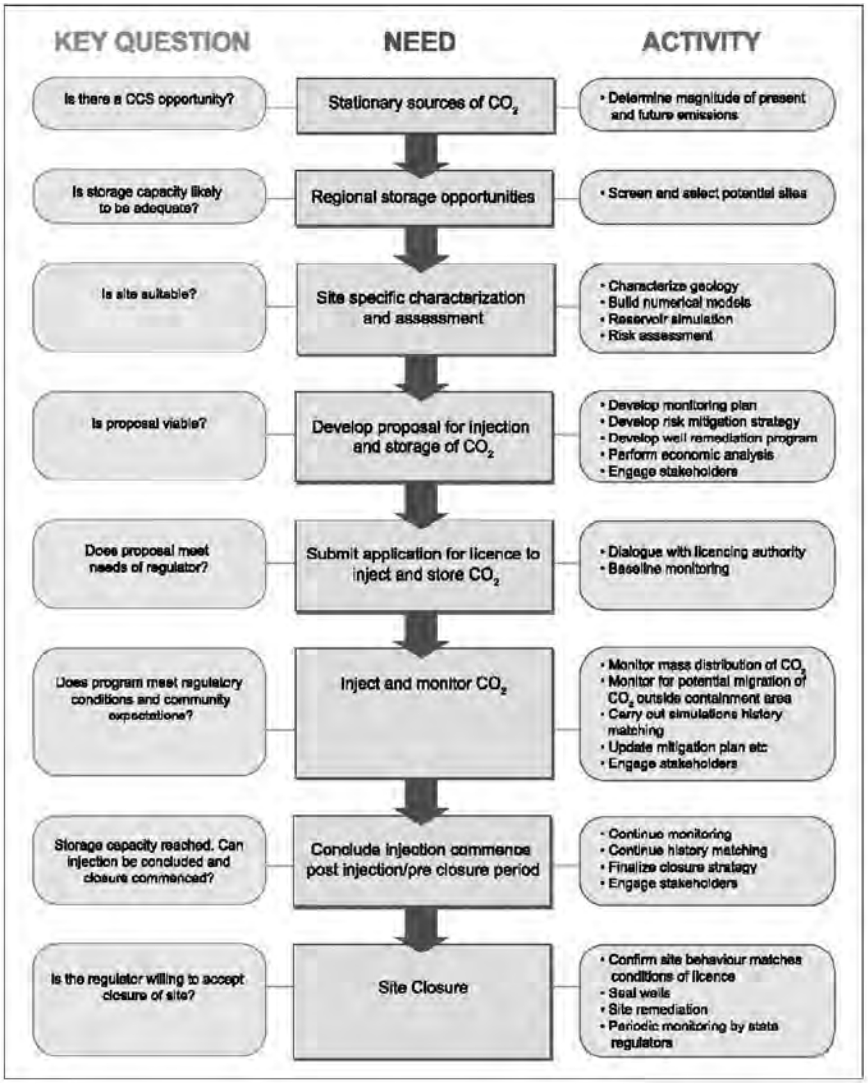

Figure 1: Life cycle of a CO_2 storage project showing the importance of integrating site characterization with a range of regulatory, monitoring, economic, risking and engineering issues.

the anticipated lifetime of the operation, to ascertain whether storage capacity can match supply volume and whether injection rates can match the supply rate.

Assigning technical risks is important for matching of CO_2 sources and storage sites, for five risk factors: storage capacity, injectivity, containment, site and natural resources (Bradshaw *et al*., 2002, 2003). These screening criteria introduce reality checks to large storage-capacity estimates and indicate which regions to concentrate upon in future detailed studies.

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.

Pipelines today operate as a mature market technology and are the most common method for transporting CO_2. Carbon dioxide 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. Road and rail tankers also are technically feasible options. 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.

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.

Carbon dioxide could leak to the atmosphere during transport, although leakage losses from pipelines are very small.

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.

Storage Capacity

Initial estimates of the capacity of known storage reservoirs (IEA GHG, 2001; IPCC, 2001) indicate that it is comparable to the amount of CO_2 which would be produced for storage by plants built and operated by electricity companies and other manufacturing enterprises through 2100.

Key Questions for Monitoring and Verification Technology

What actually happens to CO_2 in the subsurface and how do we know what is happening? In other words, can we monitor CO_2 once it is injected? What techniques are available for monitoring whether CO_2 is leaking out of the storage formation and how sensitive are they? Can we verify that CO_2 is safely and effectively stored underground? How long is monitoring needed?

Purposes for Monitoring

Monitoring is needed for a wide variety of purposes. Specifically, monitoring can be used to:

- Ensure and document effective injection well controls, specifically for monitoring the condition of the injection well and measuring injection rates, wellhead and formation pressures. Petroleum industry experience suggests that leakage from the injection well itself, resulting from improper completion or deterioration of the casing, packers or cement, is one of the most significant potential failure modes for injection projects (Apps, 2005; Perry, 2005);
- Verify the quantity of injected CO_2 that has been stored by various mechanisms;
- Optimize the efficiency of the storage project, including utilization of the storage volume, injection pressures and drilling of new injection wells;
- Demonstrate with appropriate monitoring techniques that CO_2 remains contained in the intended storage formation(s). This is currently the principal method for assuring that the CO_2 remains stored and that performance predictions can be verified;
- Detect leakage and provide an early warning of any seepage or leakage that might require mitigating action.

Technologies for Monitoring Local Environmental Effects

Monitoring of CO_2 for occupational safety is well established. On the other hand, while some promising technologies are under development for environmental monitoring and leak detection, measurement and monitoring approaches on the temporal and space scales relevant to geological storage need improvement to be truly effective.

The health of terrestrial and subsurface ecosystems can be determined directly by measuring the productivity and biodiversity of flora and fauna and in some cases indirectly by using remote sensing techniques such as hyperspectral imaging (Martini and Silver, 2002; Onstott, 2005; Pickles, 2005).

Monitoring Network Design

There are currently no standard protocols or established network designs for monitoring leakage of CO_2. Monitoring network design will depend on the objectives and requirements of the monitoring program, which will be determined by regulatory requirements and perceived risks posed by the site (Chalaturnyk and Gunter, 2005).

Long-Term Stewardship Monitoring

The purpose of long-term monitoring is to identify movement of CO_2 that may lead to releases that could impact long-term storage security and safety, as well as trigger the need for remedial action. Long-term monitoring can be accomplished with the same suite of monitoring technologies used during the injection phase. However, at the present time, there are no established protocols for the kind of monitoring that will be required, by whom, for how long and with what purpose. Geological storage of CO_2 may persist over many millions of years. The long duration of storage raises some questions about long-term monitoring.

Until long-term monitoring requirements are established (Stenhouse *et al*., 2005), it is not possible to evaluate which technology or combination of technologies for monitoring will be needed or desired.

Verification of CO_2 Injection and Storage Inventory

No standard protocols have been developed specifically for verification of geological storage. Demonstrating that CO_2 remains within the storage site, from both a lateral and vertical migration perspective, is likely to require some combination of models and monitoring.

Key Questions for Risk Management, Risk Assessment and Remediation

What are the risks of storing CO_2 in deep geological formations? Can a geological storage site be operated safely? What are the safety concerns and environmental impact if a storage site leaks? Can a CO_2 storage site be fixed if something does go wrong?

Local health, safety and environmental hazards arise from three distinct causes:

- Direct effects of elevated gas-phase CO_2 concentrations in the shallow subsurface and near-surface environment;
- Effects of dissolved CO_2 on groundwater chemistry;
- Effects that arise from the displacement of fluids by the injected CO_2.

Episodic and localized seepage will likely tend to have more significant impacts per unit of CO_2 released than will seepage that is continuous and or spatially dispersed. Global impacts arising from release of CO_2 to the atmosphere depend only on the average quantity released over time scales of decades to centuries. Second, the hazards arising from displacement, such as the risk of induced seismicity, are roughly independent of the probability of release.

Processes and Pathways for Release of CO_2 from Geological Storage Sites

Carbon dioxide that exists as a separate phase (supercritical, liquid or gas) may escape from formations used for geological storage through the following pathways:

- Through the pore system in low-permeability caprocks such as shales, if the capillary entry pressure at which CO_2 may enter the caprock is exceeded;
- Through openings in the caprock or fractures and faults;

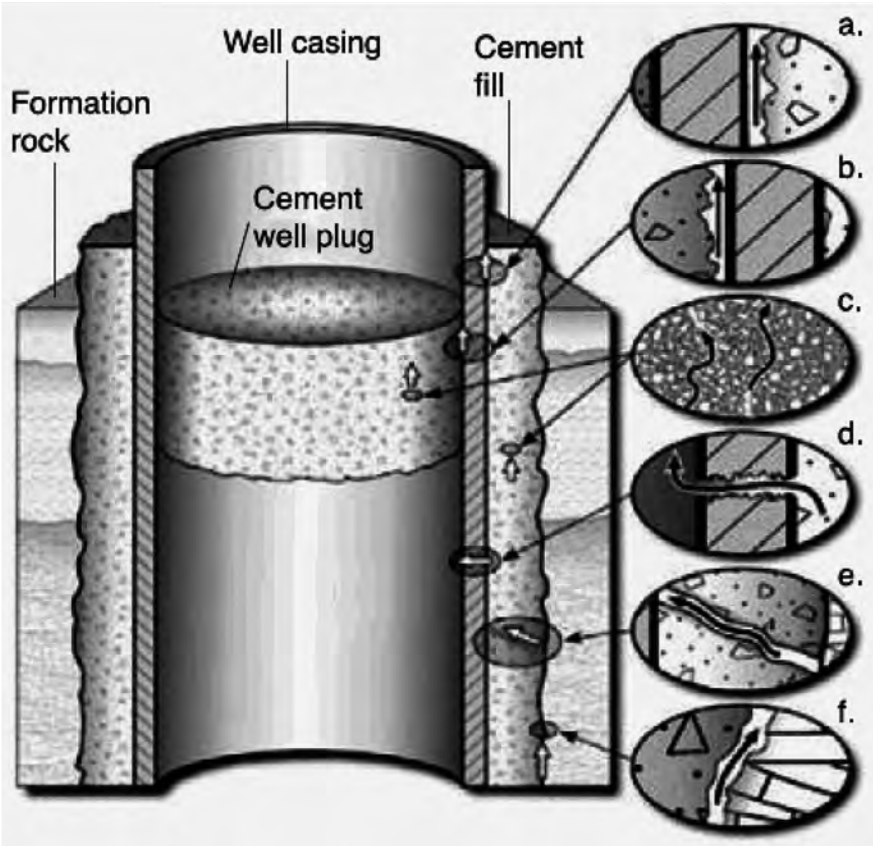

Figure 2: Possible leakage pathways in an abandoned well: (a) and (b) between casing and cement wall and plug, respectively; (c) through cement plugs; (d) through casing; (e) through cement wall; and (f) between the cement wall and rock (after Gasda* et al.*, 2004).

- Through anthropomorphic pathways, such as poorly completed and/or abandoned pre-existing wells.

Once escaping CO_2 reaches the surface layer of the atmosphere and the surface environment, where humans and other animals can be exposed to it. Carbon dioxide dispersion and mixing result from surface winds and associated turbulence and eddies. As a result, CO_2 concentrations diminish rapidly with elevation, meaning that ground-dwelling animals are more likely to be affected by exposure than are humans (Oldenburg and Unger, 2004). Calm conditions and local topography capable of containing the dense gas will tend to prevent mixing. But such conditions are the exception and in general, the surface layer can be counted on to strongly dilute seeping CO_2. Nevertheless, potential concerns related to buildup of CO_2 concentrations on calm days must be carefully considered in any risk assessment of a CO_2 storage site. Additionally, high subsurface CO_2 concentrations may accumulate in basements, subsurface vaults and other subsurface infrastructures where humans may be exposed to risk.

Injection wells and abandoned wells have been identified as one of the most probable leakage pathways for CO_2 storage projects (Gasda *et al*., 2004; Benson, 2005).

Probability of Release from Geological Storage Sites

Storage sites will presumably be designed to confine all injected CO_2 for geological time scales. Nevertheless, experience with engineered systems suggest a small fraction of operational storage sites may release CO_2 to the atmosphere. No existing studies systematically estimate the probability and magnitude of release across a sample of credible geological storage systems.

Natural Systems

Natural systems allow inferences about the quality and quantity of geological formations that could be used to store CO_2. The widespread presence of oil, gas and CO_2 trapped in formations for many millions of years implies that within sedimentary basins, impermeable formations (caprocks) of sufficient quality to confine CO_2 for geological time periods are present.

Storage security in mature oil and gas provinces may be compromised if a large number of wells penetrate the caprocks (see figure 3). Steps need to be taken to address this potential risk.

Numerical Simulations of Long-Term Storage Performance

Several CO_2 storage projects are now in operation and being carefully monitored. While no leakage of stored CO_2 out of the storage formations has been observed in any of the current projects, time is too short and overall monitoring too limited, to enable direct empirical conclusions about the long-term performance of geological storage.

Possible Local and Regional Environmental Hazards

Risks to human health and safety arise (almost) exclusively from elevated CO_2 concentrations in ambient air, either in confined outdoor environmentnds, in caves or in buildings. Physiological and toxicological responses to elevated CO_2 concentrations are relatively well understood (see appendix 3.3 from IPCC report). At concentrations above about 2%, CO_2 has a strong effect on respiratory physiology and at concentrations above 7–10%, it can cause unconsciousness and death. Exposure studies have not revealed any adverse health effect of chronic exposure to concentrations below 1%. Because CO_2 is 50% denser than air, it tends to migrate downwards, flowing along the ground and collecting in shallow depressions, potentially creating much higher concentrations in confined spaces than in open terrain.

Hazards to Groundwater from CO_2 Leakage and Brine Displacement

Increases in dissolved CO_2 concentration that might occur as CO_2 migrates from a storage reservoir to the surface will alter groundwater chemistry, potentially affecting shallow groundwater used for potable water and industrial and agricultural needs. Dissolved CO_2 forms carbonic acid, altering the pH of the solution and potentially causing indirect effects, including mobilization of (toxic) metals, sulphate or chloride; and possibly giving the water an odd odor, color or taste. In the worst case, contamination might reach dangerous levels, excluding the use of groundwater for drinking or irrigation.

Hazards to Terrestrial and Marine Ecosystems

Stored CO_2 and any accompanying substances, may affect the flora and fauna with which it comes into contact. Impacts might be expected on microbes in the deep subsurface and on plants and animals in shallower soils and at the surface. In the last three decades, microbes dubbed 'extremophiles,' living in environments where life was previously considered impossible, have been identified in many underground habitats.

The working assumption may be that unless there are conditions preventing it, microbes can be found everywhere at the depths being considered for CO_2 storage and consequently CO_2 storage sites may generally contain microbes that could be affected by injected CO_2. Should CO_2 leak from the storage formation and find its way to the surface, it will enter a much more biologically active area. While elevated CO_2 concentrations in ambient air can accelerate plant growth, such fertilization will generally be overwhelmed by the detrimental effects of elevated CO_2 in soils, because CO_2 fluxes large enough to significantly increase concentrations in the free air will typically be associated with much higher CO_2 concentrations in soils.

There is no evidence of any terrestrial impact from current CO_2 storage projects. Likewise, there is no evidence from EOR projects that indicate impacts to vegetation such as those described above. However, no systematic studies have occurred to look for terrestrial impacts from current EOR projects.

Induced Seismicity

Underground injection of CO_2 or other fluids into porous rock at pressures substantially higher than formation pressures can induce fracturing and movement along faults (Healy *et al*., 1968; Gibbs *et al*., 1973; Raleigh *et al*., 1976; Sminchak *et al*., 2002; Streit *et al*., 2005; Wo *et al*., 2005). Induced fracturing and fault activation may pose two kinds of risks. First, brittle failure and associated microseismicity induced by overpressuring can create or enhance fracture permeability, thus providing

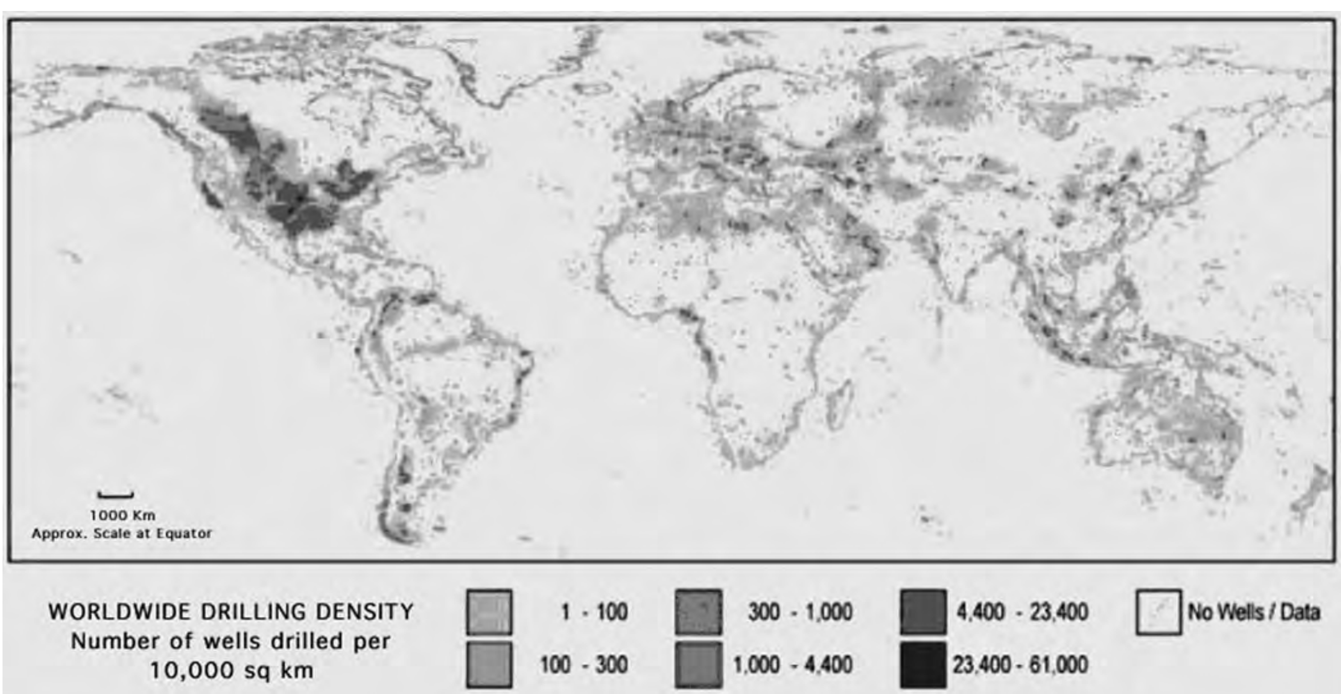

Figure 3: World oil and gas well distribution and density (courtesy of IHS Energy).

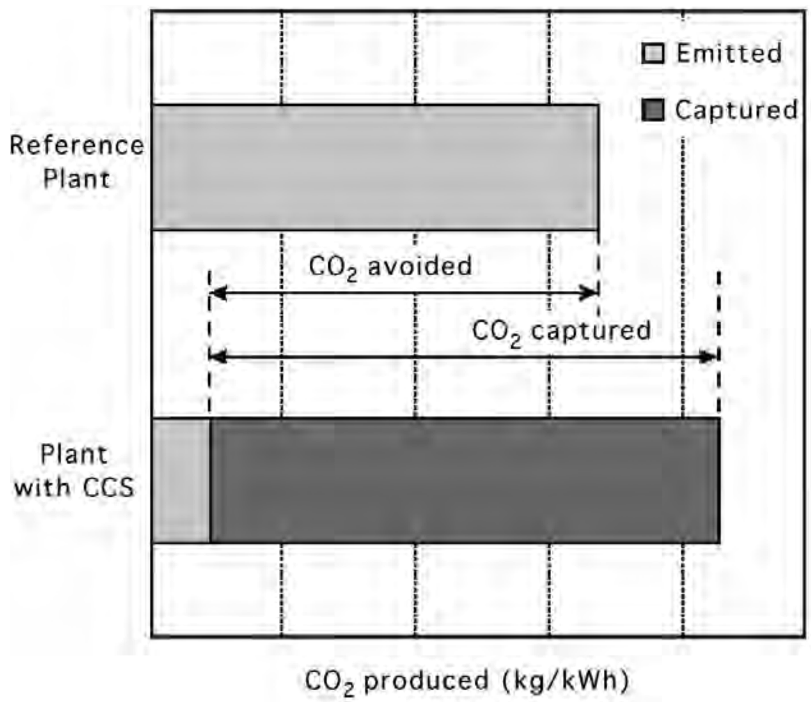

Figure 4: CO_2 capture and storage from power plants. The increased CO_2 production resulting from loss in overall efficiency of power plants due to the additional energy required for capture, transport and storage, and any leakage from transport result in a larger amount of CO_2 produced per unit of product (lower bar) relative to the reference plant (upper bar) without capture.

pathways for unwanted CO_2 migration (Streit and Hillis, 2003). Second, fault activation can, in principle, induce earthquakes large enough to cause damage (e.g., Healy *et al*., 1968). More experience with industrial-scale CO_2 storage projects will be needed to fully assess risks of microseismicity.

National Regulations and Standards

Regulating CO_2 storage presents a variety of challenges: the scale of the activity, the need to monitor and verify containment and any leakage of a buoyant fluid and the long storage time—all of which require specific regulatory considerations.

An analysis of existing regulations in North America, Europe, Japan and Australia highlights the lack of regulations that are specifically relevant for CO_2 storage and the lack of clarity relating to post-injection responsibilities (IEA-GHG, 2003; IOGCC, 2005).

In the United States, the Safe Drinking Water Act regulates most underground injection activities. The USEPA Underground Injection and Control (UIC) Program, created in 1980 to provide minimum standards, helps harmonize regulatory requirements for underground injection activities. The explicit goal of the UIC program is to protect current and potential sources of public drinking water. The Safe Drinking Water Act expressly prohibits underground injection that 'endangers' an underground source of drinking water. Endangerment is defined with reference to national primary drinking water regulations and adverse human health effects. For certain types or 'classes' of wells, regulations by the USEPA prohibit injection that causes the movement of any contaminant into an underground source of drinking water.

Long-Term Liability

A number of novel issues arise with CO_2 geological storage. In addition to long-term *in situ* risk liability, which may become a public liability after project decommissioning, global risks associated with leakage of CO_2 to the atmosphere may need to be considered. Current injection practices do not require any long-term monitoring or verification regime. The cost of monitoring and verification regimes and risk of leakage will be important in managing liability. There are also considerations about the longevity of institutions and transferability of institutional knowledge. If long-term liability for CO_2 geological storage is transformed into a public liability, can ongoing monitoring and verification be assured and who will pay for these actions? How will information on storage locations be tracked and disseminated to other parties interested in using the subsurface? What are the time frames for storage? Is it realistic (or necessary) to put monitoring or information systems in place for hundreds of years?

Any discussion of long-term CO_2 geological storage also involves intergenerational liability and thus justification of such activities involves an ethical dimension. Some aspects of storage security, such as leakage up abandoned wells, may be realized only over a long time frame, thus posing a risk to future generations. Assumptions on cost, discounting and the rate of technological progress can all lead to dramatically different interpretations of liability and its importance and need to be closely examined.

Costs of Geological Storage

Energy and economic models are used to study future scenarios for CCS deployment and costs. These 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.

The major components of a CCS system include capture (separation plus compression), transport and storage (including measurement, monitoring and verification). In one form or another, these components are commercially available. However, there is relatively little commercial experience with configuring all of these components into fully integrated CCS systems at the kinds of scales which would likely characterize their future deployment. The literature reports a fairly wide range of costs for employing CCS systems with fossil-fired power production and various industrial processes. The range spanned by these cost estimates is driven primarily by site-specific considerations such as the technology characteristics of the power plant or industrial facility, the specific characteristics of the storage site, and the required transportation distance of CO_2. In addition, estimates of the future performance of components of the capture, transport, storage, measurement and monitoring systems are uncertain. The literature reflects a widely held belief that the cost of building and operating CO_2 capture systems will fall over time as a result of technological advances.

For the studies listed in the IPCC report, CO_2 capture increases the cost of electricity production by 35–70% (0.01 to 0.02 US$/kWh) for an natural gas combined-cycle (NGCC) plant, 40–85% (0.02 to 0.03 US$/kWh) for a supercritical pulverized coal (PC) plant, and 20–55% (0.01 to 0.02 US$/kWh) for an integrated gasification combined cycle (IGCC) plant. Overall, the electricity production costs for fossil fuel plants with capture (excluding CO_2 transport and storage costs) ranges from 0.04–0.09 US$/ kWh, as compared to 0.03–0.06 US$/kWh for similar plants without capture.

The cost of employing a full CCS system for electricity generation from a fossil-fired power plant is dominated by the cost of capture. The application of capture technology would add about 1.8 to 3.4 US$/kWh^{-1} to the cost of electricity from a PC power plant, 0.9 to 2.2 US$/kWh^{-1} to the cost for electricity from an IGCC coal power plant, and 1.2 to 2.4 US$/kWh^{-1} from a NGCC power plant. Transport and storage costs would add between –1 and 1 US$/kWh^{-1} to this range for coal plants, and about half as much for gas plants. The negative costs are associated with assumed offsetting revenues from CO_2 storage in EOR or ECBM projects. Typical costs for transportation and geological storage from coal plants would range from 0.05–0.6 US$/kWh^{-1}.

The commercial basis of conventional CO_2-EOR operations is that the revenues from incremental oil compensate for the additional costs incurred (including purchase of CO_2) and provide a return on the investment.

There is limited information on monitoring costs.

No estimates have been made regarding the costs of remediation for leaking storage projects.

Long-Term Economic Impact

An increasing body of literature has been analyzing short- and long-term financial requirements for CCS. The World Energy Investment Outlook 2003 (IEA, 2003) estimates an upper limit for investment in CCS technologies for the OECD of about US$ 350 to 440 billion over the next 30 years, assuming that all new power plant installations will be equipped with CCS.

Public Perception and Acceptance

From this limited research, it appears that at least three 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; (3) the public has to accept this technology as a non-harmful and effective option that will contribute to the resolution of (1) and (2).

Acceptance of the three conditions does not imply support for CO_2 capture and storage. The technology may still be rejected by some as too 'end of pipe,' treating the symptoms not the cause, delaying the point at which the decision to move away from the use of fossil fuels is taken, diverting attention from the development of renewable energy options and holding potential long-term risks that are too difficult to assess with certainty. Conversely, there may be little realization of the practical difficulties in meeting existing and future energy needs from renewables. Acceptance of CO_2 capture and storage, where it occurs, is frequently 'reluctant' rather than 'enthusiastic' and in some cases reflects the perception that CO_2 capture and storage might be required because of failure to reduce CO_2 emissions in other ways. Furthermore, several of the studies above indicate that an 'in principle' acceptance of the technology can be very different from acceptance of storage at a specific site.

Knowledge Gaps

Knowledge regarding CO_2 geological storage is founded on basic knowledge in the earth sciences, on the experience of the oil and gas industry (extending over the last hundred years or more) and on a large number of commercial activities involving the injection and geological storage of CO_2 conducted over the past 10–30 years. Nevertheless, CO_2 storage is a new technology and many questions remain. Here, we summarize what we know now and what gaps remain.

1. Current storage capacity estimates are imperfect:

- There is need for more development and agreement on assessment methodologies.
- There are many gaps in capacity estimates at the global, regional and local levels.

2. Overall, storage science is understood, but there is need for greater knowledge of particular mechanisms, including:
   - The kinetics of geochemical trapping and the long-term impact of CO_2 on reservoir fluids and rocks.
   - The fundamental processes of CO_2 adsorption and CH_4 desorption on coal during storage operations.

3. Available information indicates that geological storage operations can be conducted without presenting any greater risks for health and the local environment than similar operations in the oil and gas industry, when carried out at high-quality and well-characterized sites. However, confidence would be further enhanced by increased knowledge and assessment ability, particularly regarding:
   - Risks of leakage from abandoned wells caused by material and cement degradation.
   - The temporal variability and spatial distribution of leaks that might arise from inadequate storage sites.
   - Microbial impacts in the deep subsurface.
   - Methods to conduct end-to-end quantitative assessment of risks to human health and the local environment.

4. There is strong evidence that storage of CO_2 in geological storage sites will be long term; however, it would be beneficial to have:
   - Quantification of potential leakage rates from more storage sites.
   - Reliable coupled hydrogeological-geochemical-geo–mechanical simulation models to predict long-term storage performance accurately.
   - Reliable probabilistic methods for predicting leakage rates from storage sites.
   - Further knowledge of the history of natural accumulations of CO_2.
   - Effective and demonstrated protocols for achieving desirable storage duration and local safety.

5. Monitoring technology is available for determining the behavior of CO_2 at the surface or in the subsurface; however, there is scope for improvement in the following areas:
   - Quantification and resolution of location and forms of CO_2 in the subsurface, by geophysical techniques.
   - Detection and monitoring of subaquatic CO_2 seepage.
   - Remote-sensing and cost-effective surface methods for temporally variable leak detection and quantification, especially for dispersed leaks.
   - Fracture detection and characterization of leakage potential.
   - Development of appropriate long-term monitoring approaches and strategies.

6. Mitigation and remediation options and technologies are available, but there is no track record of remediation for leaked CO_2. While this could be seen as positive, some stakeholders suggest it might be valuable to have an engineered (and controlled) leakage event that could be used as a learning experience.

7. The potential cost of geological storage is known reasonably well, but:
   - There are only a few experience-based cost data from non-EOR CO_2 storage projects.
   - There is little knowledge of regulatory compliance costs.
   - There is inadequate information on monitoring strategies and requirements, which affect costs.

8. The regulatory and responsibility or liability framework for CO_2 storage is yet to be established or unclear. The following issues need to be considered:
   - The role of pilot and demonstration projects in developing regulations.
   - Approaches for verification of CO_2 storage for accounting purposes.
   - Approaches to regulatory oversight for selecting, operating and monitoring CO_2 storage sites, both in the short and long term.
   - Clarity on the need for and approaches to long-term stewardship.
   - Requirements for decommissioning a storage project.

Additional information on all of these topics would improve technologies and decrease uncertainties, but there appear to be no insurmountable technical barriers to an increased uptake of geological storage as a mitigation option.

Endnotes:

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