From workshop proceedings, "The 10-50 Solution: Technologies and Policies for a Low-Carbon Future."
The Pew Center on Global Climate Change and the National Commission on Energy Policy.

Carbon Dioxide Capture and Storage in Underground Geologic Formations

Sally M. Benson
Lawrence Berkeley National Laboratory
Berkeley, California 94720
510-235-6354: smbenson@lbl.gov

Introduction

Over the past several hundred years, atmospheric CO_2 concentrations have steadily increased and have now risen to over 370 ppm from the pre-industrial level of 280 ppm. Increases in CO_2 concentrations are attributed mainly to burning coal, oil and natural gas for electrical generation, transportation, industrial and domestic uses. Today, globally, over 20 billion tons of CO_2 are emitted into the atmosphere and of that, 5.5 billion tons are from the U.S. alone. There is growing consensus that increases in CO_2 concentrations will disrupt the earth's climate, cause sea level to rise enough to flood many low-lying coastal regions, and damage sensitive ecosystems. Experts believe that to avoid significant disruption of the climate system and ecosystems, CO_2 concentrations must be stabilized within the next several decades. At today's emission rates, atmospheric CO_2 concentrations will continue to grow rapidly and, within 50 years, may exceed the levels needed to protect sensitive ecosystems and avoid flooding in low-lying coastal areas. This situation is even more dire when we consider that over the next fifty years CO_2 emissions are expected to double as the developing world's economies grow and the standard of living increases. To address this challenge, we need a multi-pronged approach to decreasing CO_2 emissions – more efficient production and use of energy, solar power, wind energy, biomass, switching to fuel sources with lower or negligible CO_2 emissions, and Carbon Capture and Storage (CCS), the subject of this paper.

CCS in underground geologic formations is unique among the options for reducing CO_2 emissions because it offers the promise for continuing to use proven reserves of fossil fuels in a CO_2 constrained future. The basic idea behind CCS is that CO_2 is captured before it is emitted into the atmosphere and then injected deep underground where it would remain for thousands of years or longer. The idea of CCS was first developed in the late 1970's but did not get much attention until the late 1980's when scientists and engineers began to look earnestly for ways to reduce CO_2 emissions to the atmosphere. In that short time it has emerged as one of the most promising options for deep reductions in CO_2 emissions. So much so that, in fact, today 1 million tons of CO_2 is being stored annually at the Sleipner Project beneath the North Sea. Several more commercial projects are in the advanced stage of planning: the In Salah project in Algeria, the Gorgon Project in Australia, and the Snohvit Project in the continental shelf offshore of Norway. In addition to these, more are under development.

The benefits of CCS are most applicable to large stationary CO_2 emissions such as those from coal and gas-fired electrical generation plants. Electrical generation plants account for about 35% of U.S. emissions today. The United States has abundant supplies of inexpensive coal which could provide a secure supply of electricity for hundreds of years. However, per Megawatt-hour (MWh) of electrical generation, conventional coal-fired power plants emit nearly twice the CO_2 of a modern natural gas combined cycle power plant. By eliminating CO_2 emissions with CCS, these abundant coal resources could assure a stable supply of energy for many generations to come. Emissions from large industrial sources of CO_2 such as refineries, cement factories, chemical processing, and smelting plants are also suitable for CCS. Importantly, in the future, it may also be possible to use CCS to reduce CO_2 emissions from the transportation sector (which account for nearly 35% of emission in the United States) if gasification of fossil fuels is used to produce hydrogen as a transportation fuel. The U.S. Department of Energy has announced plans to build a demonstration plant that would produce both electricity and hydrogen fuel from coal, while using CCS to eliminate CO_2 emissions to the atmosphere. If this is successful, CCS may accelerate the development of the infrastructure and technology for a CO_2-free hydrogen-based transportation system.

CO_2 Capture and Storage Technology

CCS is a four-step process where: first, a pure or nearly pure stream of CO_2 is captured from flue gas or other process stream; next it is compressed to about 100 atmospheres; it is then transported to the injection site; and finally, it is injected deep underground into a geological formation such as an oil and gas reservoir where it can be safely stored for thousands of years or longer (see Figure 1).

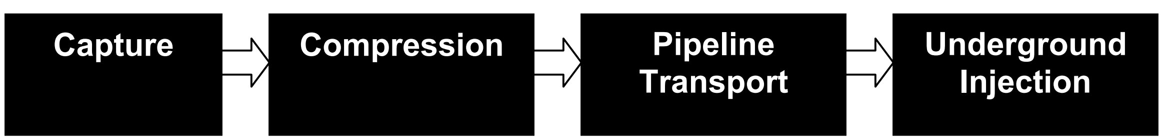

Figure 1. Schematic showing the major steps in the Carbon Capture and Storage Process.

Capture, Compression and Transportation Technology

Carbon dioxide is emitted from electrical generation plants and other combustion sources as a flue gas that contains mostly nitrogen and only from 5 to 15% carbon dioxide. Before it can be injected underground, the CO_2 must be separated from the remainder of the gas. Because of the low concentration of CO_2 in the gas, separating it is expensive, requires large surface facilities, and a lot of energy. For CO_2 capture from power generation or industrial boilers, capture technologies are grouped according to whether the CO_2 is captured after the fossil fuel is combusted, so-called post combustion capture ("end-of-pipe"), or prior to combustion (pre-combustion) in which chemical processes are used to gasify the fossil fuel to extract H_2 before it is combusted. Alternatively, from power stations, capture can be accomplished by using oxygen instead of air to combust the fossil fuels, thereby producing emissions of only CO_2 and water, from which the CO_2 is easily separated. Each of these capture technologies has benefits and drawbacks, which are summarized in Table 1 (for more details and cost data see Simbeck (2004), this volume). Of these separation technologies, only post-combustion capture is considered to be a well developed technology. In short, post-combustion capture using amine solutions is a demonstrated technology that could be applied broadly today, but costs and energy demands are high. The alternatives to post-combustion capture have significant advantages but more research, development and demonstration projects are needed before they are likely to be adopted by the power generation industry (Simbeck, 2004). Consequently, there is an urgent need for public and private investment in these new technologies.

Compression and transport of CO_2 are well established technologies that are used routinely today for enhanced oil recovery, beverage carbonation, and fire suppression. Regulations have been developed for the safe handling and transportation of CO_2 in industrial settings.

Table 1. Comparative benefits of post-combustion, pre-combustion and oxygen-combustion.

Technology	Advantages	Drawbacks
Post-Combustion	• Mature technology for other applications (e.g. separation of CO_2 from natural gas) • Standard retrofit of existing power generation capability • Technology improvements and cost reductions possible with additional development	• High energy penalty (~30%) • High cost
Pre-Combustion	• Lower costs than post-combustion capture • Lower energy penalties than post-combustion capture • High pressure of CO_2 reduces compression costs • Combine with H_2 production for transportation sector • Technology improvements and cost reductions possible with additional development	• Complex chemical process required for gasification • Repowering of existing capacity needed • Large capital investment needed for repowering
Oxygen-Combustion	• Avoid the need for complex post-combustion separation • Potentially higher generation efficiencies • Technology improvements and cost reductions possible with additional development	• New high temperature materials are needed for optimal performance • On-site oxygen separation unit needed • Repowering of existing capacity needed

Injection and Storage Technology in Underground Formations

Carbon dioxide can be injected underground and stored in sedimentary basins (see Figure 2). Sedimentary basins are created by the gradual deposition and compaction of sediments that have eroded from mountains. Deposits, as thick as tens of thousands of feet, have accumulated in sedimentary basins around the world. Typically, sedimentary basins consist of alternating layers of coarse (sandstone) and fine-textured sediments (clay, shale or evaporites[1]). The sandstone layers, which provide the storage reservoir, have high permeability, allowing the CO_2 to be injected. The shale or evaporites layers have very low permeability and act as seals to prevent CO_2 from rapidly returning to the surface. Interestingly, naturally occurring CO_2 reservoirs exist in North America, Australia, China and Europe, proving that CO_2 can be stored underground for hundreds of thousands, even millions of years. In addition, many oil and gas reservoirs also contain large quantities of CO_2 confirming that oil and gas reservoirs can also store CO_2 over geologic time scales. The technology to inject CO_2 underground is mature and practiced routinely in CO_2 enhanced oil recovery projects. Little to no new injection technology will be required to enable CCS.

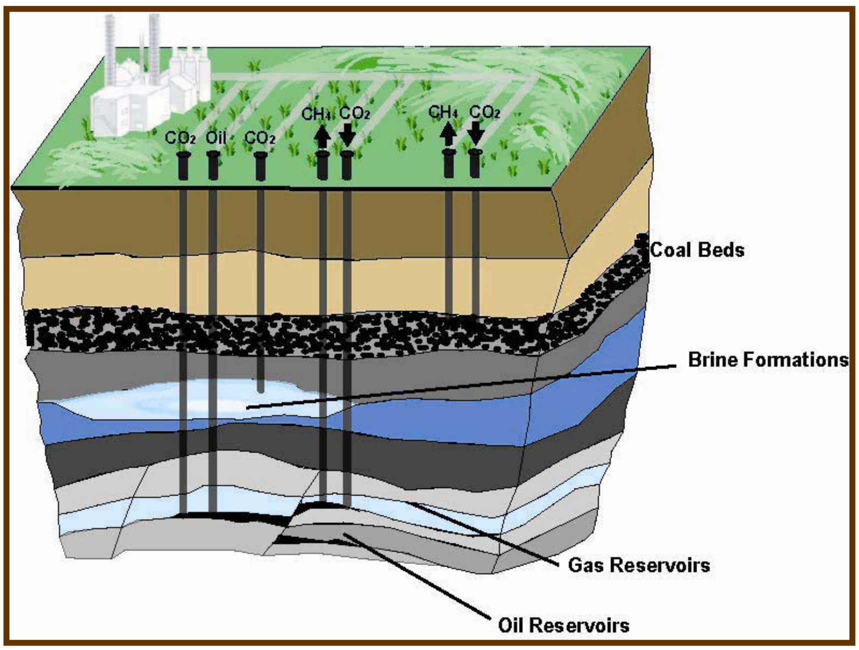

Figure 2. Schematic of a sedimentary basin with CCS. Enhanced oil and gas recovery from oil and gas reservoirs and deep unminable coal seams are also illustrated.

To ensure storage and capture integrity, locations for underground geologic storage of CO_2 would need to be selected to ensure that CO_2 would remain safely underground for thousands of years or longer. Regions with seismic or volcanic activity that could compromise the security of the storage site should not be selected. The best storage reservoirs are at depths of greater than 3000 feet below the ground surface, have several hundred feet of porous and permeable sands, and are overlain by at least one, and preferably more, thick and continuous seals. Under these conditions, CO_2 would be stored very securely and efficiently, with the density and physical properties of a liquid. Government regulations will need to be established and enforced to ensure that satisfactory sites such as these are selected for CO_2 storage.

Burruss (2004, this volume) describes how depleted oil and gas reservoirs are especially promising early opportunities for long-term storage because they have seals with 3-dimensional closure that have stood the test of time and a comparatively small effort will be needed to evaluate their storage potential. They are also attractive because CO_2 storage can be combined with CO_2 enhanced oil and gas recovery—a mature practice that is applicable to an estimated 80% of oil reservoirs. During the early stages of a storage project, the remaining oil can be extracted from the reservoir. Eventually, oil production will stop and the reservoir can be filled to capacity for long-term storage of carbon dioxide. The availability of an abundant low-cost supply of CO_2 could be a boon to the domestic oil industry. A similar idea can be applied to enhance the recovery of natural gas from deep coal beds. Tests of this concept are underway in the San Juan Basin in New Mexico. Similarly, it may be possible to increase production from natural gas reservoirs (Oldenburg et al., 2001).

Sandstone formations filled with salt water, such as the Mount Simon Formation in the Midwest, the Frio Formation along the Texas Gulf Coast, and the Central Valley in California, are estimated to have much greater storage capacity than oil and gas reservoirs. However, as pointed out by Burruss (2004), a significant effort will be required to characterize the storage reservoirs in salt-water filled formations and more importantly, to characterize the low permeability rocks that form the seal. The technology to characterize salt-water filled formations and their seals has already been developed for an analogous purpose, storage of natural gas to accommodate fluctuations in daily and seasonal demand. In the United States, natural gas is stored deep underground at over 400 sites, including over 50 aquifer storage sites, which are essentially identical to the salt-water filled formations that are contemplated for CO_2 storage. Natural gas storage technology is very similar to CO_2 storage and its successful application lends credence to the idea that CO_2 can be safely and effectively stored in salt-water filled formations.

The above discussion only focused on the potential for physically trapping carbon dioxide in deep geologic formations. Long-term storage is even more secure when the CO_2 dissolves in water or is converted to minerals such as calcium carbonate. From 10 to 30% of the injected CO_2 will usually dissolve into the formation water shortly after it is injected. For some storage sites, calculations have predicted that all of the CO_2 would dissolve within several thousand years. Once the CO_2 dissolves in the liquid, some fraction of that will be converted to minerals that will remain trapped over geologic time scales of millions of years.

Sophisticated 3-dimensional computer models are used to predict the performance of underground storage projects. While reservoir simulation is a mature technology, the capability of today's models needs to be extended to include accurate representation of the geochemical and geomechanical processes that are important for long-term storage. These models need to be validated by a number of site-specific studies that cover the range of geologic settings that could be used for CCS. International cooperation in computer simulation development and code intercomparison is helping to spur rapid improvements[2].

Current and Planned Capture and Storage Projects

Today there are four active geologic storage projects and at least two more are planned (see Table 2). These demonstrate the range of current experience with CCS. In all but two of these projects, the source of the CO_2 is natural gas. CO_2 is separated from the natural gas because some natural gas reservoirs contain too much CO_2 to sell on the open market unless the CO_2 is removed first. Motivation for injecting CO_2 underground, in contrast to emitting it to the atmosphere, was a $50 per ton CO_2 emission tax, in the case of Norway, and good environmental stewardship in the others. In addition to these projects, which were developed for the specific purpose of CCS, about 20 million tons per year of CO_2 is injected annually to recover oil from over 50 oil fields, primarily from carbonate formations in West Texas.

All the CO_2 storage projects listed in Table 2 are being used to one degree or another as demonstration projects. International teams of scientists, funded by private and government sources, are deploying monitoring technologies, computer simulation models and risk assessment methods to assess the safety of these projects, improve our understanding of geologic storage and develop advanced technologies for monitoring CO_2 storage projects. None of these existing projects is as large as would be required to capture and store the 8 million tons per year of CO_2 from a typical 1000 MW coal-fired power plant. However, the scale-up of individual projects ranging from the 1 to 4 million tons per year to 8 million tons per year should be achievable and these projects provide substantial experience on which future projects can build.

Storage Requirements and Capacity

Predicting how much CO_2 needs to be captured and stored in order to stabilize atmospheric CO_2 concentrations at safe levels is very difficult. The large number of variables such as future population growth, world-wide prosperity and standard of living, diffusion of new energy technologies, continued use of fossil fuels, natural carbon cycle dynamics and human behavior all contribute to the uncertainty in predicting CCS requirements. Nevertheless, a number of studies have attempted to address these questions and most agree that trillions of tons of storage could be needed over the next several hundred years. Annual CCS requirements could peak in the range of 10 billion tons of CO_2 per year by the end of the next century.

Table 2. Summary of current and planned CCS projects.[3]

Project (Operator)	**Application**	**Mass of CO_2 Million Tons/yr**	**Capture Technology**	**Storage Formation**
Sleipner, North Sea (Statoil)	Storage of CO_2 stripped from natural gas	1 since 1996	Amine-Scrubber	Off-shore salt-water sand formation
Weyburn, Canada (Encana)	EOR and CO_2 storage from coal gasification	1.7 since 2000	Pre-combustion Gasification	On-shore oil reservoir in carbonate rock
In Salah, Algeria (BP)	Storage of CO_2 stripped from natural gas	1 planned for 2004	Amine-Scrubber	On-shore gas reservoir in sandstone
Gorgon, Australia (ChevronTexaco)	Storage of CO_2 stripped from natural gas	4 planned for 2006	Amine-Scrubber	Island salt-water sandstone formation
Snohvit, Off-shore Norway (Statoil)	Storage of CO_2 stripped from natural gas	0.7 planned for 2006	Amine-scrubber	Off-shore salt-water sandstone formation
San Juan Basin, New Mexico (Burlington)	Enhanced coal-bed methane production		Natural CO_2 Source	On-shore coal bed

World-wide, national, and regional estimates of storage capacity have been attempted over the past decade by a number of research groups. Global results are summarized in Table 3. While the range of estimates is large, there is consensus that the largest potential capacity is in deep salt-water filled sandstones in large sedimentary basins. In fact, it is estimated that salt-water filled formations have the capacity to accommodate hundreds of years at current CO_2 emission rates. However, these capacity estimates have not yet been validated by regional or site-specific field experiments. As pointed out by Burruss (2004), better estimates may be available for oil and gas reservoirs. Burruss estimates that depleted oil and gas reservoirs in the U.S. have 40 to 50 years of storage capacity at today's emission rates. Similar conclusions have been drawn for international and regional studies. The limited capacity of oil and gas reservoirs and the lack of co-location with many existing power plants necessitates that rapid progress be made to quantify the capacity and identify suitable storage sites in salt-water filled formations. It is interesting to note that the majority of CCS projects today are in salt-water formations. The lack of nearby sites or infrastructure for EOR and the expediency of using co-located salt-water formations made this the preferable option. Whether this trend is coincidental or a precursor of future choice remains to be seen.

Table 3. Summary of world-wide storage capacity estimates.

Formation Type	Capacity Estimate (Gt CO_2)	Source
Depleted oil and gas reservoirs	~ 450 Gt	Stevens et al., 2001: GHGT 6 pp. 278-283
Coal-bed methane reservoirs	60 - 150 Gt	Stevens et al., 1999: GHGT 5 pp. 175-180
Salt-water filled formations	300 - 10,000 Gt	IEA Greenhouse Gas R&D Programme, 1994

The issue of co-location is an important one and will play a major role in which types of formations are selected for geologic storage. Figure 3 shows the location of the largest CO_2 sources in the U.S. overlain on the distribution of oil and gas reservoirs, deep coal beds and salt-water formations. In some areas, such as the Texas Gulf Coast, the Rocky Mountain Region and the Western United States, oil, gas, and salt-water formations are all available. In the Midwest and northeast, deep salt-water formations are the primary option. If a large interconnected pipeline infrastructure were built to transport CO_2 between regions, co-location of sources and sinks would not be the primary determinant of which type of formation was used for storage. Perhaps more importantly, Burruss (2004, this volume) surmises that eventually, new large power stations will be sited specifically for co-location with attractive storage sites, such as large oil and gas reservoirs. This would require an extensive network of CO_2 transport pipelines, with distances extending up to several thousand miles. While this at first may appear overly ambitious, it is not so unlikely given that today we have over 180,000 miles of natural gas pipelines in the United States[4] and over 1100 miles pipelines transporting CO_2 from the four corners areas into West Texas for CO_2 enhanced oil recovery[5].

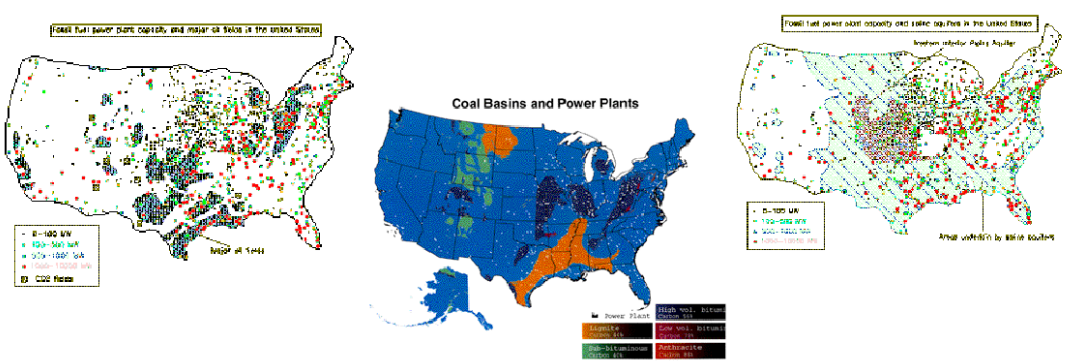

Figure 3. Location of major power sources and potential storage formations.

In summary, current estimates suggest that sufficient storage capacity will be able to accommodate decades, and probably centuries, of anthropogenic CO_2 emissions. Estimates in oil and gas reservoirs are the most reliable – which is fortunate since these may well be the best sites for large scale CCS in the near term. Capacity estimates in salt-water formations are very large but must be validated, in much the same way that "known reserves" are established for oil and gas resources.

Potential Risks to Humans, Resources and the Environment

Carbon dioxide is generally regarded as a safe, non-toxic, inert gas. It is an essential part of the fundamental biological processes of all living things. It does not cause cancer, affect development, or suppress the immune system in humans. However, CO_2 is a physiologically active gas that is integral to both respiration and acid-base balance in all life, and exposure to high concentrations can be harmful and even fatal. Ambient atmospheric concentrations of CO_2 are currently about 370 ppm. Humans can tolerate increased concentrations with no physiological effects for exposures up to 1% CO_2 (10,000 ppm).

Carbon dioxide is used in a wide variety of industries: from chemical manufacture to beverage carbonation and brewing, from enhanced oil recovery to refrigeration, and from fire suppression to inert-atmosphere food preservation. Because of its extensive use and production, the hazards of CO_2 are well known and routinely managed. Engineering and procedural controls are well established for dealing with the hazards of compressed and cryogenic CO_2. Carbon dioxide is regulated by Federal and State authorities for many different purposes, including occupational safety and health, ventilation and indoor air quality, confined-space hazard and fire suppression, as a respiratory gas and food additive. Current occupational safety regulations are adequate for protecting workers at CO_2 separation facilities and geologic storage sites.

The potential public health and environmental risks of CCS are believed to be well understood based on analogous experience from the oil and gas industry, natural gas storage, and the EPA's Underground Injection Control Program. For CCS, the highest probability risks are associated with leakage from the injection well itself, abandoned wells that provide short-circuits to the surface and inadequate characterization of the storage site—leading to smaller than expected storage capacity or leakage into shallower geologic formations. Potential consequences from failed storage projects include leakage from the storage formation, CO_2 releases back into the atmosphere, groundwater and ecosystem damage. Avoiding these consequences will require careful site selection, environmental monitoring and effective regulatory oversight. Fortunately, for the highest probability risks, that is, damage to an injection well or leakage up an abandoned well, methods are available to avoid and remedy these problems. In fact, many of risks are well understood based on the analogous experience listed above, and over time, practices and regulations have been put in place to ensure that most of these industrial analogues can be carried out safely.

To summarize, implemented on a small scale, in a well characterized geologic setting, geologic storage poses no unique or poorly understood risks. However, after the best characterized sites are utilized, significant characterization and risk assessment effort will be needed to accommodate additional CO_2 storage. Burruss (2004) estimates that 0.5 GtC per year (current annual emissions from electrical generations in the United States) could be stored in depleted oil and gas reservoirs for the next 50 years before the capacity is depleted. Similar or even greater amounts of CO_2 could be stored in salt-water filled formations that are shown to have high quality seals during this period. During the early phases of implementing CCS, additional sites that are less well characterized can be evaluated to establish "proven" storage reserves.

Monitoring and Verification of CCS Projects

Ensuring that CCS is safe and effective will require regulatory oversight, careful management of site selection and acquisition of monitoring data, and verification of CO_2 emission reductions. Credible monitoring and verification may well be the single-most important means of gaining public acceptance for geologic storage of CO_2. Five primary types of measurements provide the foundation for monitoring and verification of CCS:

- Measurement of CO_2 concentrations in the workplace (separation facility and wellfield) to ensure worker and public safety;
- Measurement of emissions from the capture system and surface facilities to verify emission reductions;
- Measurement of CO_2 injection rates, which are used to determine how much CO_2 has been injected into the underground formation – if enhanced oil recovery is taking place concurrent to CO_2 storage, any CO_2 produced with the oil must be monitored to calculate the net storage;
- Measurement of the condition of the well using well logs and wellhead pressure measurements; and
- Measurement of the location of the plume of CO_2 as it fills up the storage formation. This type of measurement can also be used as an early warning system in the event that CO_2 is leaking out of the storage reservoir.

It is also possible to measure surface fluxes of CO_2 using methods developed for studying the natural cycling of CO_2 between the atmosphere and the Earth's surface, but these measurements may not be used routinely due to the very low probability that CO_2 would be released back into the atmosphere from the storage reservoir. Nevertheless, they are available and have sufficient sensitivity to detect CO_2 leaks in that the event that they reach the surface. Deploying surface flux monitoring may be helpful in building public confidence in CO_2 storage.

Of the five monitoring requirements listed above, the first four are very well developed because the measurement technology can be borrowed directly from a variety of other applications, including electrical generation plants, the oil and gas industry, natural gas storage, disposal of liquid and hazardous waste in deep geologic formations, groundwater monitoring, food preservation and beverage industries, fire suppression and ecosystem research.

The fifth, monitoring plume migration, is somewhat more challenging because the sensitivity and resolution of existing measurement techniques need to be evaluated and perhaps improved. In addition, certain types of plumes, namely, narrow vertical plumes of rising CO_2 may be difficult to detect (Myer, 2003). Today, seismic imaging is the primary method for monitoring migration of CO_2 plumes in geologic storage projects. Seismic imaging technology was developed for oil and gas exploration and more recently, application has been extended to track CO_2 migration. When repeated on a periodic basis, differences in the images can be used to detect the location of CO_2. Seismic imaging is similar to the technology used to generate sonograms for medical applications, but carried out on a much larger scale. Other techniques such as electromagnetic and gravitational measurements have lower sensitivity and resolution, but may be used in combination with seismic techniques to fine-tune the interpretation of the data or in the interim between seismic measurements. Seismic imaging (see Figure 4) has been very successful for monitoring the location of the CO_2 plume at the Sleipner West project in the North Sea. Although seismic imaging has been used very successfully at Sleipner, more studies are needed in a wide variety of geologic settings to demonstrate that this technology has widespread applicability.

Because monitoring and verification of geologic storage is likely to be very important for gaining public acceptance of CCS, research and demonstration in this area is a very high priority. Pilot projects, ranging from small to large scales, are needed to demonstrate the accuracy, reliability and sensitivity of existing techniques. In addition, research is needed to develop new cost effective techniques that may provide even greater levels of assurance. In particular, more methods for providing early warning that a storage project is failing would be valuable. It is also important to conduct these pilot and demonstration projects in a wide variety of geologic settings because the accuracy and sensitivity of monitoring techniques differs in different geologic environments.

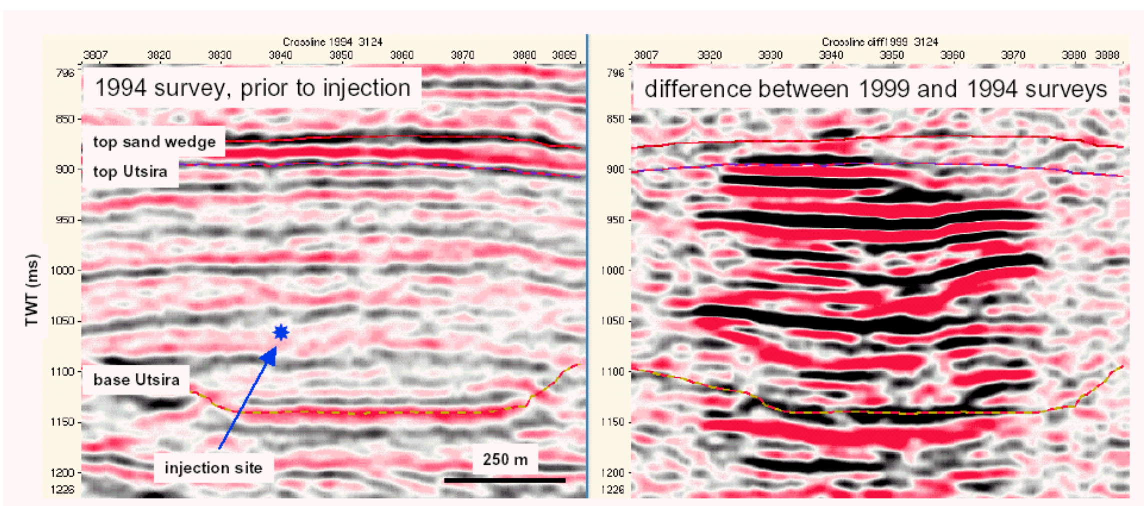

Figure 4. Seismic image of the plume of CO_2 injected into a deep geologic formation below the sea floor in the North Sea (from Zweigel et al, 2001).

Legal and Regulatory Issues

An appropriate legal framework with effective regulatory oversight is a cornerstone of effective CCS. Laws must be in place to protect personal property and the environment, and to assign liability for failed storage projects. Regulations must be in place to select and permit storage sites, specify monitoring and verification requirements, and enable constructive engagement with potentially affected citizens and communities.

The question of permanence of CO_2 storage is one of the key regulatory and performance issues that remains to be answered. Some scientists believe that storage is needed only for several hundred years. The concept of "storage effectiveness" has been developed to quantify how much must remain underground to avoid compromising the effectiveness of geologic storage. Estimates of the required "storage effectiveness" range from about 90% in 100 years to 90% in 10,000 years (Pacala, 2003, Hepple and Benson, 2003; and Lindeberg, 2003). The range is explained by differences in assumptions about how much CO_2 is stored, atmospheric stabilization levels, future industrial emissions, economic considerations about the cost of storage, and the effectiveness of the natural carbon cycle as a CO_2 sink. Other scientists believe that geologic storage will be and should be, for all intents and purposes, "permanent." Preference for this approach is determined in part by national attitudes and partly by the belief that geologic structures could provide storage for millions of years. This author believes that from the perspective of a "climate change technology," a storage effectiveness of 90% in 1000 years is acceptable, and in fact, a conservative lower limit to the performance that is needed. However, the possibility for local groundwater and ecosystem impacts associated with leakage at this rate may argue for more permanent storage. Coming to consensus on the performance requirements, including the question of permanence, for geologic storage is an important issue that must be addressed.

There is also no consensus on whether or not adequate regulations are in place for oversight of geologic storage. Certainly, many of the building blocks are in place. Some would argue that existing regulations for CO_2 injection during enhanced oil recovery are adequate. Others would say that the EPA's Underground Injection Control Program, which regulates underground disposal of hazardous wastes, is sufficient. Others, like this author, believe that CCS is sufficiently unique and may be implemented on such a large scale to warrant its own regulatory regime. Chief among the arguments for this include the unique physical and geochemical attributes of CO_2 and the long-term storage requirement. At low concentrations, CO_2 is not hazardous and in fact essential for life, so a set of regulations based on substances that are hazardous at parts-per-billion concentrations make no sense. Similarly, injection of CO_2 for enhanced oil recovery has no requirement for long-term storage, so existing regulations provide little assurance that CO_2 would be safely stored for thousands of years or longer.

Getting started on developing a science-based regulatory approach for CCS is needed soon to allow regulatory permitting of upcoming experimental projects and begin to define a set of performance requirements against which projects can be objectively assessed.

Cost of CO_2 Capture and Storage

Currently, the high cost of CCS appears to be the largest barrier to implementation. Estimated costs for CCS range from \$30 to \$70 per tonne CO_2 depending mainly on the capture technology and concentration of CO_2 in the stream from which it is captured (Rubin and Rao, 2003). While this metric may be useful for comparing the cost of CCS with other methods of reducing CO_2 emissions, the increase in costs of electrical generation may be a more meaningful economic metric because the electrical generation sector will provide the biggest benefit from CCS.

Simbeck (2004) calculates that CO_2 capture (separation and compression) alone will increase the cost of electricity from \$43 per MWh to \$61-\$78 per MWh for new power plants and from \$17 per MWh to \$58-\$67 per MWh for existing coal plants that have already been paid off. Separation and compression typically account for over 75% of the costs of CCS, with the remaining costs attributed to transportation and underground storage. Pipeline transportation costs are highly site-specific; they depend strongly on economy of scale and pipeline length. Costs of underground storage are estimated from \$3 to \$10 per tonne CO_2.

In addition to the high cost of CCS, the "energy penalty" for capture and compression is high. The post-combustion, "end-of-pipe" capture technologies use up to 30% of the total energy produced, thus dramatically decreasing the overall efficiency of the power plant. Oxy-combustion, because it requires separation of a pure source of oxygen from air, also has a similarly high energy penalty, although eventually, new materials may off-set the energy penalty by allowing for higher temperature and consequently more efficient combustion. Pre-combustion technologies have the potential to lower energy penalties to the range of 10 to 20%, leading to higher overall efficiency and lower capture costs.

Public and privately sponsored research and development programs are aggressively trying to lower the costs of CO_2 capture. One industrial consortium, the CO_2 Capture Project, has the goal of reducing capture costs by 50% below today's baseline. Early studies in pre-, post- and oxy-combustion have all shown promise to meet the target cost reduction[6]. The U.S. Department of Energy has a cost goal of \$10 per ton CO_2. This extremely challenging target is likely to be hard to meet without significant advances in separation technology, including membrane separators and new absorbents. Outreach efforts by the Department of Energy and the National Academy of Sciences are tying to engage academic researchers with new ideas in these areas. Clearly achieving these cost reduction goals would significantly increase the probability that CCS would become a major element of our climate change technology strategy.

Establishing the viability of CCS will require a significant investment in research and demonstration projects. This author agrees with Davis (2004) who states:

> *"… four to six such demonstrations will be required, focusing on the technical issues outlined above and testing the concept in numerous operating locations. Because of the long project lead times, and the costs associated with these activities, it is imperative that these activities are*

coordinated internationally, with appropriate sharing of the findings to address public concerns about the technology."

FutureGen, the U.S. Department of Energy's flagship demonstration project for a next generation coal-fired power plant that co-produces electricity and hydrogen for transportation, is estimated to cost $1 billion dollars over a ten-year period. Assessing the viability of CCS as an option for a low-carbon future could require from four to six such demonstrations around the world at a total cost on the order of $5 billion dollars over a ten to twenty year period. Clearly international cooperation and cost-sharing between the public and private sector would greatly improve the viability and expedite initiation of these demonstration projects.

However, it is possible to significantly accelerate some of the demonstration projects and lower costs by focusing only on geologic storage, with the rational that unlike power generation and separation technology, geologic storage is highly site-specific and therefore requires multiple demonstration projects. Costs for these demonstration projects could be lowered by using existing sources of CO_2, such as from petroleum refineries or ammonia production plants that do not require costly separation. The costs for a large-scale, ten-year demonstration project would be on the order of $200 million. This expedited approach has the benefit that the projects could begin as soon as the sites were selected and the permits obtained. The combined benefits of lower overall costs and expedited assessment of geologic storage argue in favor of choosing to focus some demonstration projects exclusively on geologic storage. Four to six full scale demonstrations projects could be carried out in the United States at a cost of approximately $1 billion. Moreover, while lowering the cost of separation may be technologically more challenging, public acceptance of geologic storage may ultimately be the bigger obstacle to the viability of CCS. Again, this argues for an expedited assessment of geologic storage, carried out in parallel to full-scale demonstration of CCS technology.

Public Acceptance

CCS is a very new technology that is only now beginning to be known to the public. Over the past several years, popular science journals have published a handful of papers on the subject. Major newspapers and widely circulated news magazines have written short articles describing the concept, generally favorably, or at least with an open mind. As more people are exposed to the idea of CCS, public opinion will be shaped, but it is fair to say for now, that the public is generally not aware of the concept and have yet to form an opinion. Most likely, public debate about CCS will take place in three important forums.

First, as the United States continues to shape and refine its climate policy, CCS will retain a prominent role in the strategy, raising national awareness of the issue. Issues about economic competitiveness, international trade, policy implements and timing are likely to dominate this debate.

Second, non-governmental organizations (NGOs) with an interest in environmental policy will monitor and continue to evolve their opinions on whether or not CCS should play an important role in a low-carbon future. Key to these discussions will be possible preferences for energy efficiency and renewable energy over CCS as the optimal climate change technology policy. Any technology that prolongs the use of fossil fuels, such as CCS, may be viewed skeptically. In addition, the energy penalty for capture, particularly of post-combustion capture, may be viewed as wasteful and undesirable. Risks of local and regional environmental impacts and our ability to anticipate and avoid them will be crucial. As implementation become more imminent, the public debate will intensify and NGO's will play an important role in shaping public opinion about the relative benefits and risks of CCS.

Finally, and perhaps most importantly, on-the-ground pilot and demonstration projects will draw the interest and concern of the neighboring communities. Concerns about human safety and environmental impacts, property values, mineral and water rights will probably dominate these debates, which may be tempered in some areas, particularly where enhanced oil recovery is possible, by job opportunities, financial compensation and economic growth. Pipeline construction, particularly in new areas will also be met with these concerns.

How these three debates individually and collectively transpire will be critically important in determining whether CCS will gain public acceptance. The public must be persuaded that CCS is needed, and assured that it can be safe and effective. Laws and regulations that protect the public and the environment are critical to the success of CCS. The lack of public acceptance could become the major barrier to CCS.

Conclusions

CCS is in practice today and more is planned. Significant benefits from this approach include the ability to continue to use the plentiful and low cost fossil fuel resources that are available today – while at the same time, building a smooth economic transition to a low-carbon future. CCS builds upon a technology base developed over more than half a century by the oil and gas industry. Consequently, it is being implemented in some situations today, but significant technological improvements and cost reductions are also on the horizon, which can lead to even broader application.

Yet today, significant barriers to large-scale implementation of CCS remain. This challenge is best put into context by considering the scale of the endeavor. Imagine that by the year 2050 world-wide we will potentially need thousands of CCS projects that are each as big or bigger than the Sleipner Project. In the United States alone, CCS for our 2 billion tons of CO_2 emissions from electrical generation from fossil fuels could require 200 projects, each 10 times larger than the Sleipner project.

To support an endeavor of this scale, numerous advances are needed. Technological innovations are needed to reduce the cost of capture – better separation technologies, technological advances in turbine design to support repowering with advanced generation systems and systems optimization. Widespread use of CCS will also require large investments by the private sector and institutional commitments on the part of the government. New infrastructure is needed, both for CO_2 transportation and power generation. Retrofit of existing coal-fired plants may not be economical and CCS may need to await replacement of existing generation capacity with new plants that more efficiently capture CO_2. Research is needed to prove that the potentially huge storage capacity of salt-water filled formations can be used to safely and effectively store CO_2 for thousands of years or longer. Institutional issues such as regulatory oversight and the legal framework for CCS needs must be addressed. Key to these institutional issues is recognition and resolution of the intergenerational commitments inherent in underground geological storage of CO_2. Questions such as "Who is responsible for long-term monitoring?" and "Who is liable for the consequences and remedy should a storage project leak long into the future?" must be answered.

Today, the most significant barriers for implementing CCS are:

- High costs and energy penalties of post-combustion capture and separation;
- High capital costs of gasification re-powering and lack of experience of the electrical generation sector with gasification;
- Limited experience with large-scale geologic storage, including "proving" the estimates of storage capacity in salt-water formations;
- Uncertainty about public acceptance for CO_2 storage in geologic formations, including resistance to CCS based on preference for energy efficiency and renewables;
- Lack of appropriate legal and regulatory frameworks to support widespread application of CCS; and
- Lack of financial resources to support projects of sufficiently large scale to evaluate the viability of CCS.

Overcoming these barriers will require a concerted and persistent effort over the coming decades. Table 4 provides a roadmap of actions required over the near, mid and long-term based on assessments carried out over the past several years, including those studies cited by Davis (2004). These are achievable goals. Efforts have been initiated to address the actions listed in Table 4 by governments and several industrial consortia, but much more is needed. Success can be only assured by a sustained commitment to an adequate program of research and demonstration. In the near term, the estimated cost for achieving these goals is on the order of several billion dollars. Shared between the public and private sector, with close international cooperation to leverage R&D investments, this is a reasonable investment to develop this important option for creating a low-carbon future.

However, we must be mindful that CCS is just one of a number of options that can be used to reduce greenhouse gas emissions. End-use energy efficiency, renewable energy such as solar, hydropower, wind, biomass, and geothermal all have an important role to play. In the end, market forces should play a central role in developing the most cost-effective climate change technologies. By absorbing the cost of CO_2 emission control into the use of fossil fuels, the playing field is leveled for other energy technologies and may in fact be a boon to these alternative energy sources. No matter which path we take in the end, we must now develop a reliable and realistic portfolio of options to reduce atmospheric emissions of CO_2.

Table 4. Near, mid and long term actions needed to enable assessment and deployment of CCS as a major strategy to achieve a low-carbon future.

Near Term (0-10 years)	Mid-Term (10 to 30 years)	Long Term (> 50 years)
• Research to bring down CCS costs and develop greater assurance about the security of geologic storage • Policies that discourage continued use of existing electrical generation capacity without CO_2 controls • Demonstration of coal gasification combined with CCS • Demonstrations of geological storage at 4 to 6 sites in different geologic settings • Development of science-based regulatory approach that addresses site selection, risk assessment and long term monitoring, and clearly addresses local, regional, and NGO safety and environmental concerns	• Assessment of regional "proven" storage reserves • Research and development to improve the performance of capture systems and optimize storage in geologic formations • Policies that encourage use of low-carbon power generation technologies • Deployment of full scale CCS projects at new or repowered electricity plants with incentives to make these "show-case" projects that are highly visible and transparent to the public • Research and demonstration projects to develop hydrogen-based transportation systems • Refinement of regulatory approaches to take advantage of "learning by doing"	• Full-scale deployment of hydrogen-based transportation systems from fossil-fuels generated hydrogen • Development of large-scale infrastructure to support widespread use of CCS for both the electricity and transportation sectors • Refinement of regulatory approaches to take advantage of "learning by doing"

References

Simbeck, D. (2004) "CO2 Capture Economics." Prepared for *The 10-50 Solution: Technologies and Policies for a Low-Carbon Future, Pew Center on Global Climate Change and the National Commission on Energy Policy*, March 25-26, Washington, DC.

Burruss, R. (2004) "Geologic Sequestration of Carbon Dioxide in the Next 10 to 50 Years: An Energy Resource Perspective." Prepared for *The 10-50 Solution: Technologies and Policies for a Low-Carbon Future, Pew Center on Global Climate Change and the National Commission on Energy Policy*, March 25-26, Washington, DC.

Oldenburg, C., et al. (2001) "Process Modeling of CO_2 Injection into Natural Gas Reservoirs for Carbon Sequestration and Enhanced Gas Recovery." Energy & Fuels, Vol. 15, No. 2, pp. 293-298.

Stevens, S., et al. (2001) "Sequestration of CO_2 in Depleted Oil and Gas Fields: Global Capacity, Costs, and Barriers." *Proceedings of Greenhouse Gas Control Technologies 5th International Conference (GHGT-5),* pp. 278-283, Williams, Durie, McMullan, Paulson, and Smith (Eds.)

Stevens, S., et al. (1999) "CO2 Sequestration in Deep Coal Seams: Pilot Results and Worldwide Potential." *Proceedings of Greenhouse Gas Control Technologies 4th International Conference (GHGT-4),* pp. 175-180, Eliasson, Riemer, and Wokaun (Eds.)

Myer, L. (2003) "Sensitivity and Cost of Monitoring Geologic Sequestration using Geophysics." *Proceedings of Greenhouse Gas Control Technologies 6th International Conference (GHGT-6),* Vol. 1, pp. 377-382, J. Gale and Y. Kaya (Eds.), Elsevier Science Ltd.

Zweigel, P., et al. (2001) "Prediction of Migration of CO2 Injected into and Underground Depository: Reservoir Geology and Reservoir Modeling in the Sleipner Case (North Sea)." *Proceedings of Greenhouse Gas Control Technologies 5th International Conference (GHGT-5),* pp. 360-365, Williams, Durie, McMullan, Paulson, and Smith (Eds.)

Pacala, S. (2003) "Global Constraints on Reservoir Leakage." *Proceedings of Greenhouse Gas Control Technologies 6th International Conference (GHGT-6),* Vol. 1, pp. 267-272, J. Gale and Y. Kaya (Eds.), Elsevier Science Ltd.

Hepple, R. and S. Benson (2003) "Implications of Surface Seepage on the Effectiveness of Geologic Storage of Carbon Dioxide as a Climate Change Mitigation Strategy." *Proceedings of Greenhouse Gas Control Technologies 6th International Conference (GHGT-6),* Vol. 1, pp. 261-266, J. Gale and Y. Kaya (Eds.), Elsevier Science Ltd.

Lindeberg, E, (2003) "The Quality of a CO_2 Repository: What is the Sufficient Retention Time of CO_2 Stored Underground." *Proceedings of Greenhouse Gas Control Technologies 6th International Conference (GHGT-6),* Vol. 1, pp. 255-260, J. Gale and Y. Kaya (Eds.), Elsevier Science Ltd.

Rubin, E. and A. Rao (2003) "Uncertainties in CO_2 Capture and Sequestration Costs." *Proceedings of Greenhouse Gas Control Technologies 6th International Conference (GHGT-6),* Vol. 1, pp. 1119-1124, J. Gale and Y. Kaya (Eds.), Elsevier Science Ltd.

Davis (2004) "Gasification and Carbon Capture and Storage: The Path Forward." Prepared for *The 10-50 Solution: Technologies and Policies for a Low-Carbon Future, Pew Center on Global Climate Change and the National Commission on Energy Policy*, March 25-26, Washington, DC.

---

[1] Evaporites are sedimentary rocks that consist of salts formed by precipitation in closed water basins. They often have very low permeability and form seals for oil and gas reservoirs. Examples include sodium chloride, gypsum, anhydrite, limestone and dolomite.

[2] From 2000 to 2003 the United States Department of Energy sponsored an international code intercomparison study with participation of ten scientific teams from six different countries. The teams conducted computer simulations of seven different problems that tested the ability to simulate the physical, chemical and mechanical processes that are important for secure geologic storage of CO_2 (www-esd.lbl.gov/GEOSEQ/).

[3] Most of the experience in CCS has come from separating CO_2 from natural gas. While the experience gained on geologic storage is relevant to storage of CO_2 from electrical generation, the experience with separation is less relevant because separation of CO_2 from flue gas is more challenging than for separation from natural gas.

[4] See www.ingaa.org for a description of the natural gas transport infrastructure in the United States and the safety regulations that are used to protect public and worker safety.

[5] See www.kindermorgan.com for more information about CO_2 production from the McElmo dome and pipeline transport to West Texas for CO_2 enhanced EOR.

[6] Studies of post-combustion, pre-combustion and oxygen combustion all have shown promise for achieving target cost reductions. Follow-on experiments and studies will be needed to confirm these promising results. See www.co2captureproject.org for more information about these studies.