Commissioner Primer

Carbon Dioxide Capture and Storage

The National Regulatory Research Institute

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Partha S. Chaudhuri
Research Associate

Michael Murphy
Graduate Research Associate

Robert E. Burns
Senior Institute Attorney

Executive Summary

A contributing cause of climate change is the accumulation of greenhouse gases in the atmosphere. Carbon dioxide (CO_2) is a principal greenhouse gas which is caused, in part, by human activities such as generation of electricity from fossil fuels. Interest in CO_2 capture and storage in geologic formations (CCS) and in terrestrial carbon sequestration systems is rapidly growing. Terrestrial carbon sequestration involves locking carbon in soil or long-lived biomass such as forests. CCS systems capture CO_2 from a flue gas or a process stream, transport it to a suitable storage location, and inject it into suitable deep geologic formations for permanent storage.

Planned field tests to be conducted over the next four years under the U.S. Department of Energy's Carbon Sequestration Program are bringing to the fore issues related to the regulation of CCS and terrestrial carbon sequestration. Some state public utility commissioners are already dealing with applications for employing CCS or terrestrial carbon sequestration technologies while other state utility commissioners will likely need to address these issues in the future. While these issues will primarily affect a state commission in its role of assessing utility cost recovery, a few other issues could be within the purview of the state commission, including siting, condemnation and eminent domain, and pipeline safety. In some states, the public utility commission also acts as regulator of Class 2 underground injection wells used for the disposal of fluids associated with oil and gas production; use of similar wells for CO_2 storage is not unlikely. Implementation of CCS and terrestrial carbon sequestration will involve a number of regulatory agencies at the state and federal levels. State commission efforts at interagency coordination can increase the regulatory agency's understanding of the costs that are subject to cost recovery as well as enhance the likelihood that electric generation technologies incorporating CCS are implemented.

Contents

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In the foreseeable future, CO_2 emissions will continue to rise. Thus, the search is on for carbon abatement strategies.

CO_2 may be "sequestered"-- captured and stored by injection deep into rock formations (geological) or by putting it back in the ecosphere (terrestrial). This primer focuses primarily on the former.

INTRODUCTION

Research indicates that increasing concentrations of greenhouse gases in the atmosphere are responsible for global warming, sometimes also referred to as climate change. Carbon dioxide (CO_2) resulting from human activities is considered one of the major contributors to global warming. While efficient use of fossil energy with its eventual substitution by carbon-free energy sources may be the ultimate solution, it is evident that, in the foreseeable future, CO_2 emissions will continue to rise. Thus concerns about global climate change have led to the search for effective carbon abatement strategies.

The terrestrial biosphere is the natural carbon sink that sequesters approximately two billion metric tons of carbon per year.[1] Terrestrial carbon sequestration is the net removal of CO_2 from the atmosphere or prevention of CO_2 emissions from terrestrial ecosystems into the atmosphere. Two approaches to terrestrial carbon sequestration are: preservation of the ecosystems that store carbon and enhancement of their ability to sequester carbon beyond current levels. Prevention of deforestation and reforestation are examples of methods used for terrestrial carbon sequestration. For example, planting trees to offset the CO_2 emissions of a power plant could be an effective carbon abatement strategy.

For CO_2 point sources another alternative is to physically capture CO_2 and store it in secure geologic formations. Separation and capture of CO_2 from flue gas or process streams at chemical plants have long been in practice for the production of chemicals such as fertilizers and carbonated beverages. However, these processes are generally expensive and have only been used for the production of commodity CO_2. Research continues on cost-effective technologies applicable to high-volume gas streams with low concentration of CO_2, such as power plant flue gas, for capture and geologic storage of CO_2 to be economically viable. Underground injection of CO_2 has also been in use to enhance oil recovery from partially depleted fields or to dispose of acid gases (removed from natural gas) in depleted gas reservoirs. However, other types of geologic formations, with minimum leakage potential, will be used for CO_2 storage.

The U. S. Department of Energy (DOE) has funded seven regional partnerships to conduct pilot projects demonstrating geological CO_2 storage and terrestrial carbon sequestration within each region.[2] Battelle Memorial Institute is leading the Midwest Regional Carbon Sequestration Partnership (MRCSP).[3] The National Regulatory Research Institute (NRRI) is the research partner in the MRCSP dealing with regulatory issues associated with these technologies. This primer provides public utility regulators with an initial background on geologic CO_2 storage and terrestrial carbon sequestration and their associated regulatory issues.

This primer is an introduction to engineered CO_2 capture at a point source such as a modern power plant coupled with geologic CO_2 storage in suitable deep geologic formations such as depleted oil and gas reservoirs, coal seams and deep saline formations. The primary focus is on geologic CO_2 storage, although terrestrial carbon sequestration is dealt with briefly. This primer also provides public utility regulators with an initial background on the associated regulatory issues but does not delve into how those are to be resolved.

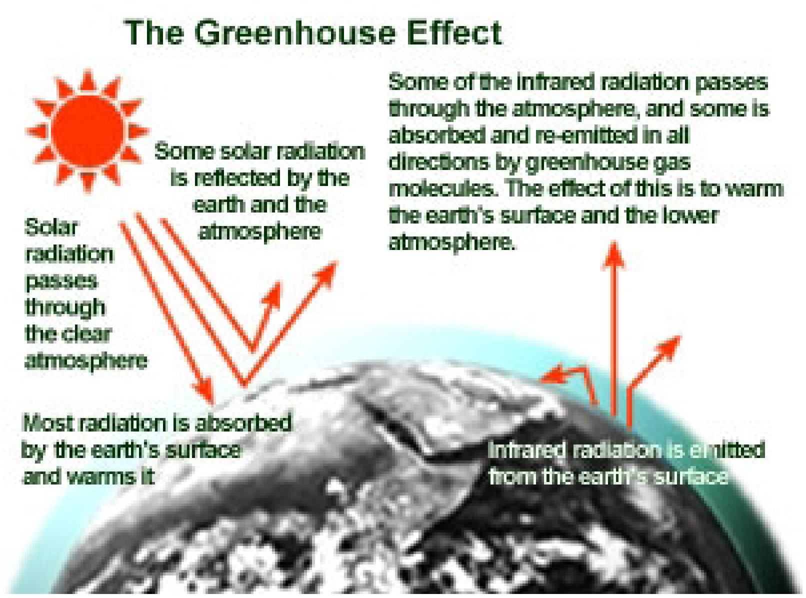
THE IMPACT OF CARBON DIOXIDE IN THE ATMOSPHERE

The National Academy of Sciences estimates that the earth's surface temperature has risen by about one degree Fahrenheit in the last century.[4] There is a growing scientific consensus that accumulation of greenhouse gases[5] in the atmosphere due to human activities is the primary cause for this change.[6] As shown in Figure 1, energy from the sun heats the earth's surface, and a portion of the energy is radiated back into the space. Greenhouse gases in the atmosphere trap some of this outgoing energy causing the earth's temperature to rise.[7]

CO_2 is one of the greenhouse gases responsible for climate change. The greenhouse gases are produced as a result of natural processes (for example, decomposition of plants, dead animals, and other organic matters) as well as human activities, such as the combustion of fossil fuels, mining of coal, extraction of oil and natural gas, the raising of livestock, deforestation,

The reader will be introduced to engineered CO_2 capture at a point source such as a modern power plant and storage in suitable geological formation.

CO_2 is one of the greenhouse gases responsible for climate change.



Source: U.S. Environmental Protection Agency.

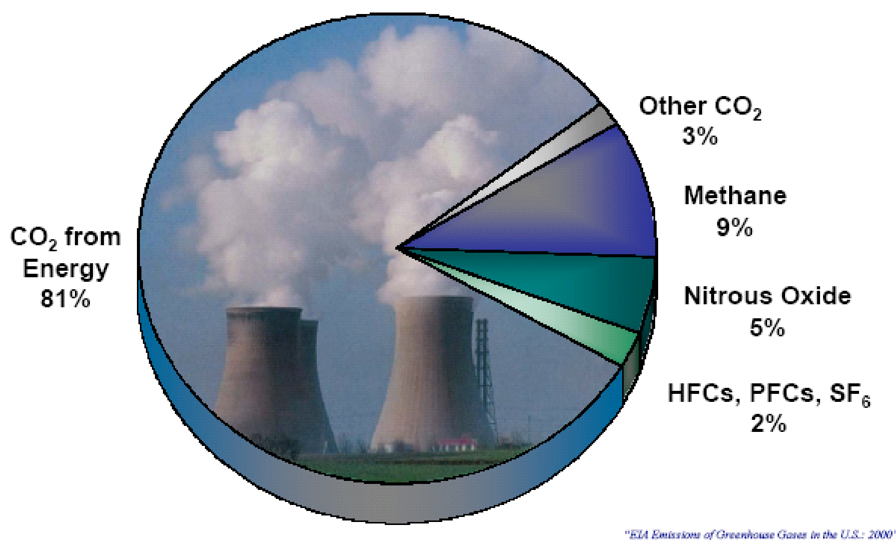
Fig. 1. The greenhouse effect.

and other agricultural and industrial activities. Figure 2 shows the different greenhouse gases emitted due to human activities in the United States.

Fossil fuels will continue to be the dominant source of energy during the rest of this century. Absent curbs on CO_2 emissions, global surface temperatures will increase and the sea level will rise.

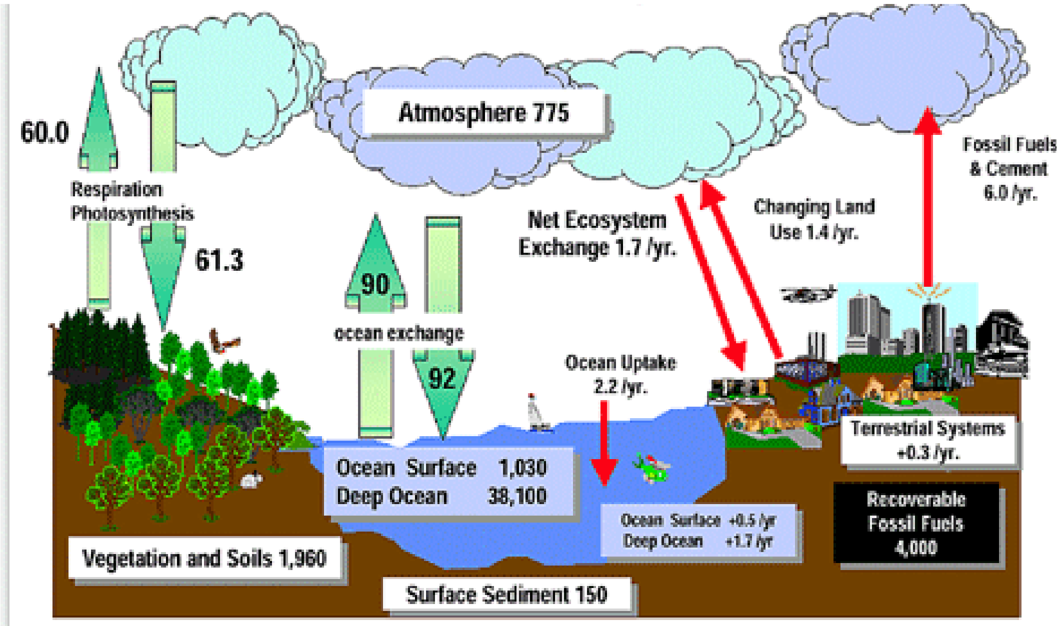
As shown in Figure 3, release and storage of carbon is part of the carbon cycle. Naturally occurring CO_2 releases—which are ten times greater than CO_2 released as a result of human activities—have generally been in balance with CO_2 absorption by ocean and terrestrial vegetation. The CO_2 released as result of human activity, also referred to as anthropogenic CO_2, causes the atmospheric concentration of CO_2 to increase which is leading to climate change. The United States CO_2 emissions by source and sector are shown in Figure 4. The CO_2 concentration in the atmosphere at present is 379 ppm (parts per million), about 33 percent above the pre-industrial level, and is rising at 1 ppm per year.[8] The 20th century's ten warmest years all occurred in the last 15 years of the century. The snow cover in the northern hemisphere and floating ice in the Arctic have decreased due to the rising temperature and the sea level, globally, has risen 4-8 inches in the past century.[9]

Fossil fuels meet 86 percent of all primary energy demand globally and are likely to remain the dominant source of energy in the next century. Globally, by 2100, absent measures to curb CO_2 emissions into the atmosphere, CO_2 concentrations are projected to be 30-150 percent higher than today's levels. Scientists predict that increasing concentration of CO_2 in the atmosphere will lead to an average global



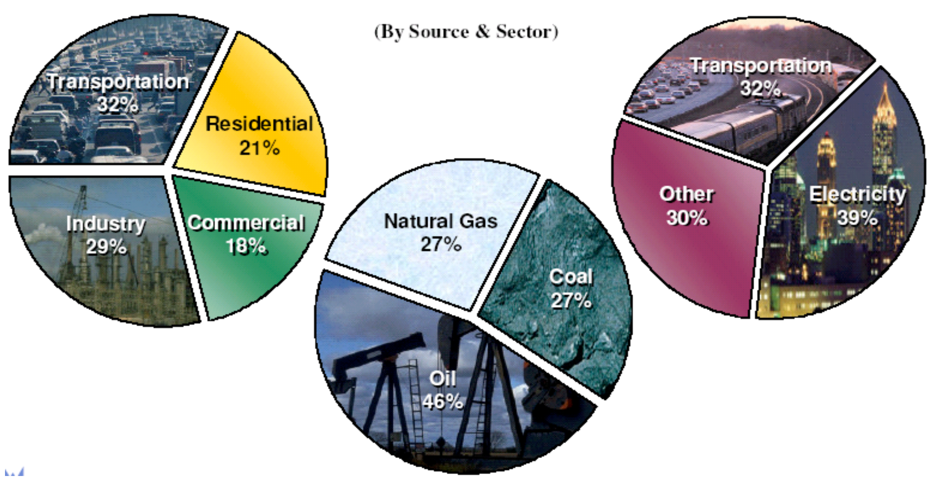
Source: National Energy Technology Laboratory (2003). Presentation by Scott Klara on U.S. DOE Field Efforts Sequestering CO2 in Geologic Formations. Available at http://www.netl.doe.gov/publications/ carbon_seq/presentations/SPE_AAPG_090803.pdf.

Fig. 2. U.S. greenhouse gas emissions (equivalent global warming basis).



Source: Prof. R. Lal, The Carbon Management and Sequestration Center of The Ohio State University.

Fig. 3. Global carbon fluxes in gigatons.



Source: National Energy Technology Laboratory (2004). Presentation by Scott Klara at the Programmatic Environmental Impact Statement Public Meeting. May 18.

Fig. 4. U.S. carbon dioxide emissions.

Reduction of CO_2 emissions into the atmosphere is receiving increasing attention globally and in the United States.

surface temperature rise of 2.2-10° F with consequential sea level rise of two feet along most of the U.S. coast.[10] Calculations of climate change for specific areas and regions are less reliable at this time, but some low lying coastal areas worldwide could be rendered uninhabitable, if these predictions come true.

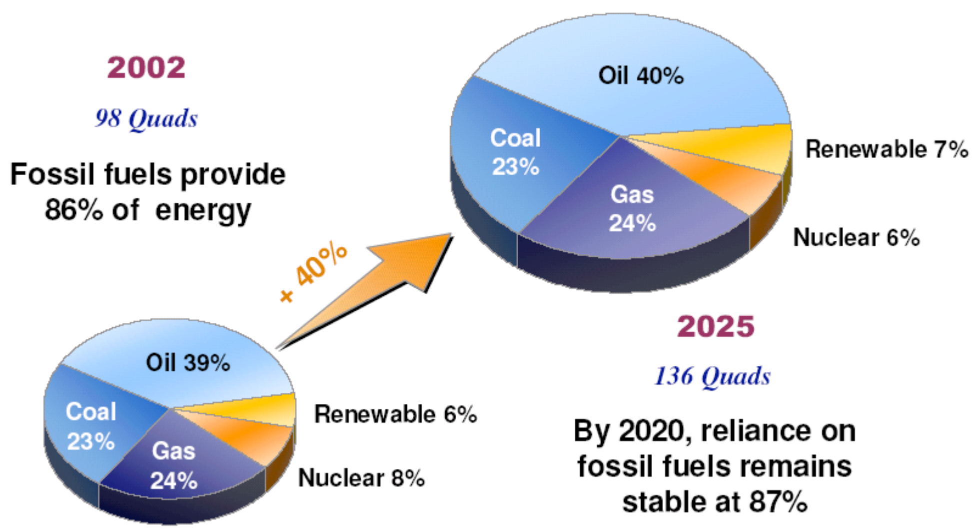
MEANS OF REDUCING CO_2 LEVELS

Reduction of CO_2 emissions into the atmosphere is receiving increasing attention globally and also in the United States which stems from the possible effects of climate change. This is achievable by:

(1) Using energy more efficiently
(2) Switching to lower carbon energy sources such as switching from coal to natural gas for power generation
(3) Deploying more carbon free energy sources (e.g., nuclear, hydro, geothermal, wind, solar, etc.)
(4) Capturing CO_2 before it can be released to the atmosphere through the application of CO_2 capture and geologic storage technologies
(5) Removing CO_2 from the atmosphere through the application of terrestrial sequestration technologies and isolating it in long-lived carbon pools (such as forest)

Although an eventual transition to carbon-free sources of energy is the ultimate goal, in the foreseeable future consumption of fossil fuels will continue to rise.

As shown in Figure 5, energy usage in the United States is anticipated to grow from 98 quads in 2002 to 136 quads in 2025—a growth of nearly 40 percent. Although during this period our reli-



Source: National Energy Technology Laboratory (2004). Presentation by Scott Klara at the Programmatic Environmental Impact Statement Public Meeting. May 18.

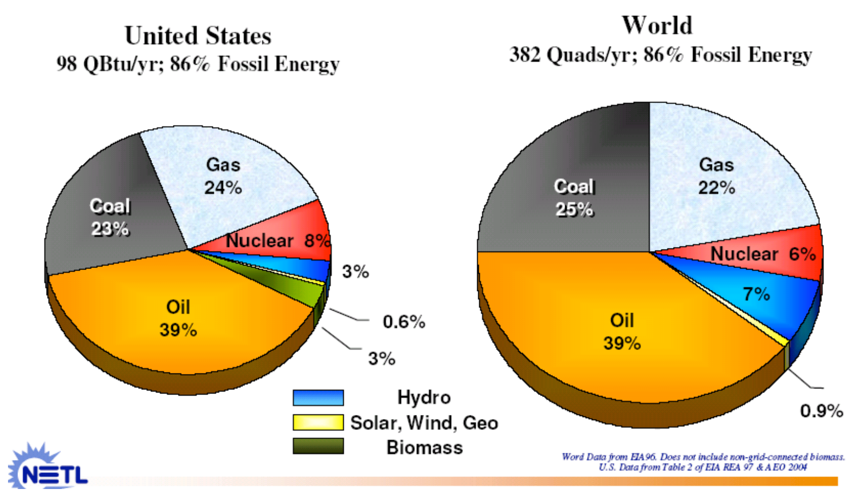
Fig. 5. U.S. energy mix.

ance on fossil fuels, on a percentage of energy used basis, remains nearly the same, greater energy consumption would translate into much larger quantities of fossil fuels being burnt. This will result in a large increase in CO_2 emissions into the atmosphere if no preventive measures are taken. But the United States is not alone in its thirst for fossil fuels. As shown in Figure 6, the world itself (including the United States) used 382 quads of energy in 2002, of which 86 percent is reliant on fossil fuels. The United States is a major emitter of anthropogenic greenhouse gases as a major user of fossil fuels and thus has greater responsibility to address climate change.[11] However, given that climate change is a global problem and energy use, population, and standards of living are all expected to continue growing over the course of this century, CO_2 emissions are expected to rise across the globe. Figure 7 shows the contribution of different countries and regions to global anthropogenic CO_2 emissions in 2002. Therefore, all nations and all sectors must eventually participate in efforts to address climate change through reducing their emissions of greenhouse gases into the atmosphere.[12]

In this primer, we address options for capturing, transporting, and storing CO_2 in suitable deep geologic formations. In some cases, these steps today face significant costs. For example, the process of capture, transportation, and injection of CO_2 can consume significant amounts of energy. Production of this additional energy in turn requires use of additional fuel that results in more CO_2 being produced, unless of course this additional energy is produced from nuclear or renewable sources. As a result, more than a ton of CO_2 will have to be captured to have the same overall effect as avoiding a ton of CO_2 emissions. Whether the

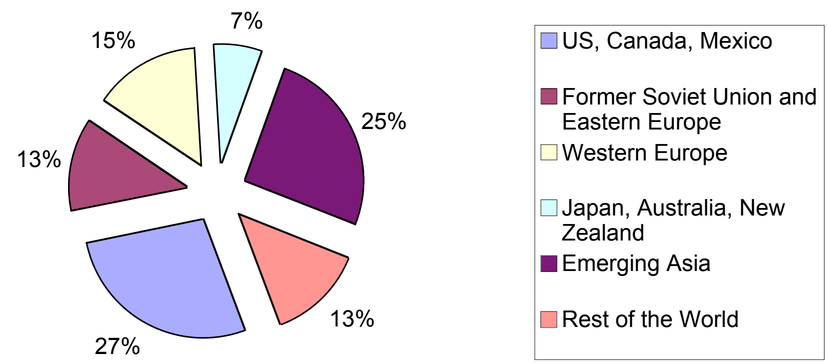
All nations and sectors must eventually participate in the effort to address climate change through reductions in emissions of greenhouse gases.

Because carbon sequestration itself uses energy, more than a ton of CO_2 will have to be captured to have the same effect as avoiding a ton of CO_2 emissions. Whether the cost is worth it is the subject of ongoing debate.



Source: Annual Energy Outlook 2004 cited in National Energy Technology Laboratory (2004). Presentation by Scott Klara at the Programmatic Environmental Impact Statement Public Meeting. May 18.

Fig. 6. World energy mix 2002.



Source: Based on data from Department of Energy (2005).

Fig. 7. Global anthropogenic CO_2 emissions in 2002 (percent).

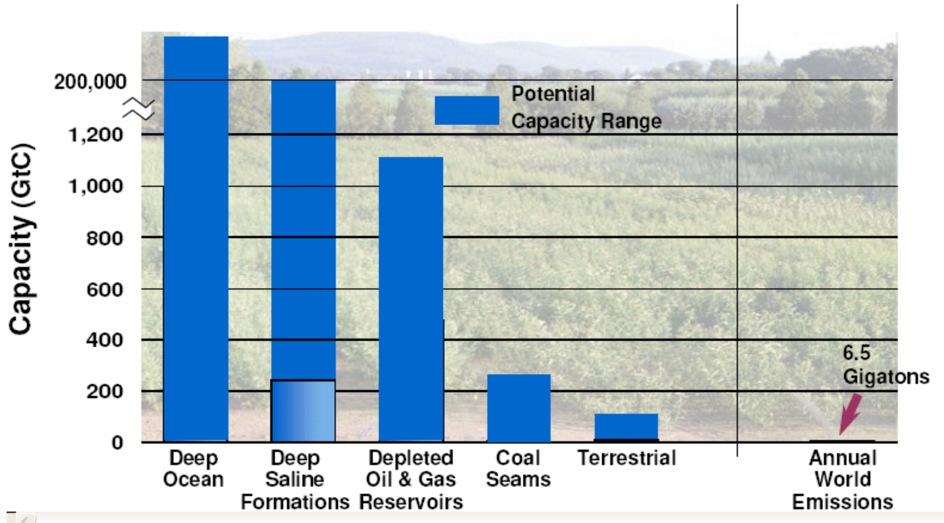
benefit of this action is worth the cost is an ongoing debate among scientists, economists, public interest groups, politicians and the general public that we will not delve into.

Geologic CO_2 capture and storage (CCS) for an electric power plant burning coal comprises of:

- *Capture—isolation of the CO_2*
- *Compression*
- *Transportation to a storage site*
- *Injection into storage wells*

CARBON DIOXIDE CAPTURE AND STORAGE IN GEOLOGIC FORMATIONS (CCS)

Capturing CO_2 for geologic storage as a method of preventing its release to the atmosphere applies only to point sources of CO_2, such as an electric generating plant burning coal. The process involves isolation of CO_2 (capture) from the flue gas (or from the fuel before combustion), its compression and transportation to the storage site, and injection into the storage wells. Candidate deep geologic formations suitable for long-term storage of CO_2 include depleted oil and gas reservoirs, unmineable coal seams, and underground saline formations. The estimated potential worldwide storage capacity for each of these options (as well as terrestrial carbon sequestration potential) is shown in Figure 8. The storage capacity is shown in gigatons (GtC) or billion tons of carbon (1 GtC is equivalent to 3.67 $GtCO_2$). At present there are two commercial-scale CCS projects in operation—one in Norway and the other in Algeria. Both of these projects involve storage of CO_2 separated from natural gas in deep saline aquifers. A third project closely resembling CCS is in operation in the United States where CO_2 captured at the Dakota Synfuels Plant is transported to Weyburn oilfields in Canada for enhanced oil recovery (EOR).[13]



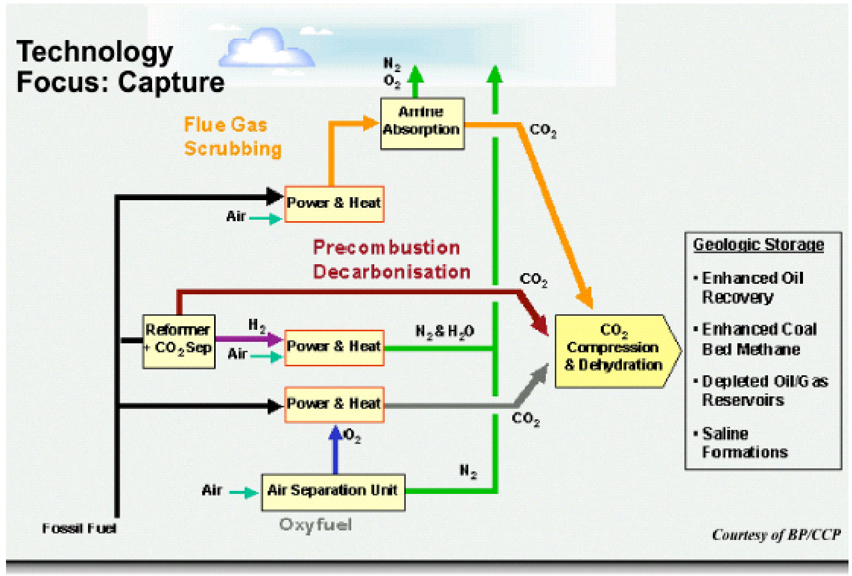
Source: National Energy Technology Laboratory (2004). Presentation by Scott Klara at the Programmatic Environmental Impact Statement Public Meeting. May 18.

Fig. 8. Large potential worldwide carbon storage capacity.

Capture of CO_2 at Source

As shown in Figure 9, before CO_2 can be stored in geological formations it must be isolated at its source, such as a fossil fuel burning power plant, as a relatively pure gas. The flue gas resulting from the combustion of fossil fuels in air usually contains a small percentage of CO_2, a large amount of nitrogen and oxides of nitrogen as well as various other gases formed due to the combustion of other noncarbon constituents of the fuel. Preferential absorption of CO_2 by a solvent, such as monoethanolamine, is the method most commonly used for CO_2 capture. The solvent is then regenerated to strip the dissolved CO_2, which results in a highly concentrated stream of CO_2. Using this method CO_2 is routinely captured from industrial processes such as synthetic ammonia production, hydrogen production, and limestone calcinations for use as chemical raw material. However, the high cost of this method of capture makes its use impractical for the purpose of geologic storage of CO_2 that does not yield a financial return. The process is applicable where the captured CO_2 is used as a production input, such as for the production of carbonated beverages, fertilizers, or EOR because it has a commodity value that justifies the costs associated with the capture of CO_2. CO_2 is the nineteenth largest commodity chemical, on a mass basis, in the United States. With the solvent absorption method for the capture of CO_2, it is estimated that capture, in and of itself, would constitute three-fourths of the total cost of CCS. Innovative and more cost-effective schemes for the separation of CO_2 have been proposed, but they are still largely in the research and development phase.

The high cost of CO_2 capture using a solvent makes this method impractical if there is no financial return.



Flow diagram of various CO_2 capture and storage technologies

Source: National Energy Technology Laboratory (2003).

Fig. 9. Pre and post-combustion capture of CO_2 for geologic storage.

Oxyfuel combustion might have some cost advantages over air firing.

Pre-combustion capture of CO_2 is feasible for integrated coal gasification combined cycle plants.

The concentration of CO_2 in the flue gas of power plants typically ranges from 3 percent (natural gas fired) to 15 percent (coal fired), depending on the carbon content of the fuel; the remainder is primarily nitrogen. Replacing air with oxygen for the combustion of the fuel (oxyfuel combustion) would result in a much higher concentration of CO_2 in the flue gas and, consequently, reduce the CO_2 capture costs. However, production of oxygen from air involves another separation process and may consume up to 15 percent of the power plant's output. Given that the byproducts from the oxygen separation process—nitrogen, argon, and others—are saleable products, and assuming continued technological advance and a need to employ CCS systems to address climate change, some researchers estimate that oxyfuel combustion might have some cost advantages over air firing.[14]

Pre-combustion capture of CO_2 is feasible for integrated coal gasification combined cycle plants where coal is gasified using oxygen to produce synthesis gas (CO + H_2). Synthesis gas can be further processed to produce CO_2 and hydrogen. The CO_2 from the stream is captured using physical solvents (such as Selexol). The hydrogen and part of CO_2 are sent to drive a turbine coupled to an electricity generator, and the remainder of CO_2 is transported for use as feedstock or for geologic storage.[15] A somewhat similar application of this concept is at the North Dakota Synfuels Plant that employs coal gasification technology. The CO_2 from the process stream is captured and transported via pipeline to the Weyburn oilfield in Saskatchewan, Canada for EOR.[16]

Transportation of CO_2 for Storage

CO_2 can be transported as liquid in tankers or in supercritical phase via pipeline. Pipeline transport as a supercritical fluid is likely the most cost effective and reliable when dealing with large quantities as would be required for CCS. However, for transportation over long distances (exceeding 625 mi or 1000 km), ocean tankers may have a cost advantage when ship transportation is a viable alternative. Land-based pipelines are likely to be the cheapest option in the continental United States and are likely to be the dominant means of moving CO_2 if and when CCS is implemented. There are many CO_2 pipelines in operation in the United States, the earliest of which was built nearly 35 years ago. There are more than 1,500 miles of main and lateral pipelines in the United States and Canada carrying over 55 million tons per year of CO_2 to oilfields.[17] These pipelines primarily transport naturally occurring CO_2 to oil fields for EOR, with the exception of the most recently-built 205-mile long pipeline from the North Dakota Synfuels Plant (referenced above) to Canada that transports CO_2 captured from the synthesis fuel production process and closely resembles the proposed pipelines for CCS.

For pipeline transport, the captured CO_2 is compressed to above 1250 psi, cooled and dehydrated before transportation. At this pressure CO_2 exists in supercritical phase and behaves as a liquid; however, its specific properties require the compressors, pipelines and associated equipment to have some special features such as corrosion resistance, special seals, etc. Otherwise the design practices governing natural gas pipelines generally apply to CO_2 pipelines. CO_2 pipelines operate at 1250-2270 psia and 40-100^{o} F.[18] Compression cost is the main component of the transportation cost.

CO_2 pipelines are classified by the U.S. Department of Transportation (DOT) (en) as high volatile, low hazard, low risk; however, if a leak develops, CO_2 may accumulate in low lying areas and, at concentrations in the 7-10 percent range by volume, asphyxiation can occur; a 20-30 minute exposure at concentrations above 20 percent can be fatal.[19] CO_2 is also colorless and odorless like natural gas. The risks of accidental exposure can be mitigated through addition of odorants (mercaptans) to CO_2, maintenance of adequate safety distances from inhabited areas in routing the pipeline and frequent use of block valves (to isolate the affected section of the pipe and minimize CO_2 discharge), and the application of commercial best practices such as supervisory control and data acquisition systems. Proven design methods are available for safe installation and operation of CO_2 pipelines and the statistics of pipeline incidents indicate that CO_2 pipelines are no more hazardous than natural gas pipelines.

CO_2 Storage in Geologic Formations

Depleted oil and gas reservoirs are considered one of the suitable geologic formations that can be used for CO_2

Land-based pipelines are likely to be the dominant means of moving CO_2 to storage if and when CCS is implemented.

Compression cost is the main component of transportation cost.

Proven design methods are available for safe installation and operation of CO_2 pipelines.

Potential storage sites include:

- ***Depleted oil and gas reservoirs***
- ***Unmineable coal seams***
- ***Deep subterranean and sub-seabed saline formations***

The most prevalent storage option will be injection into deep saline formations, which are widespread and have large storage potential.

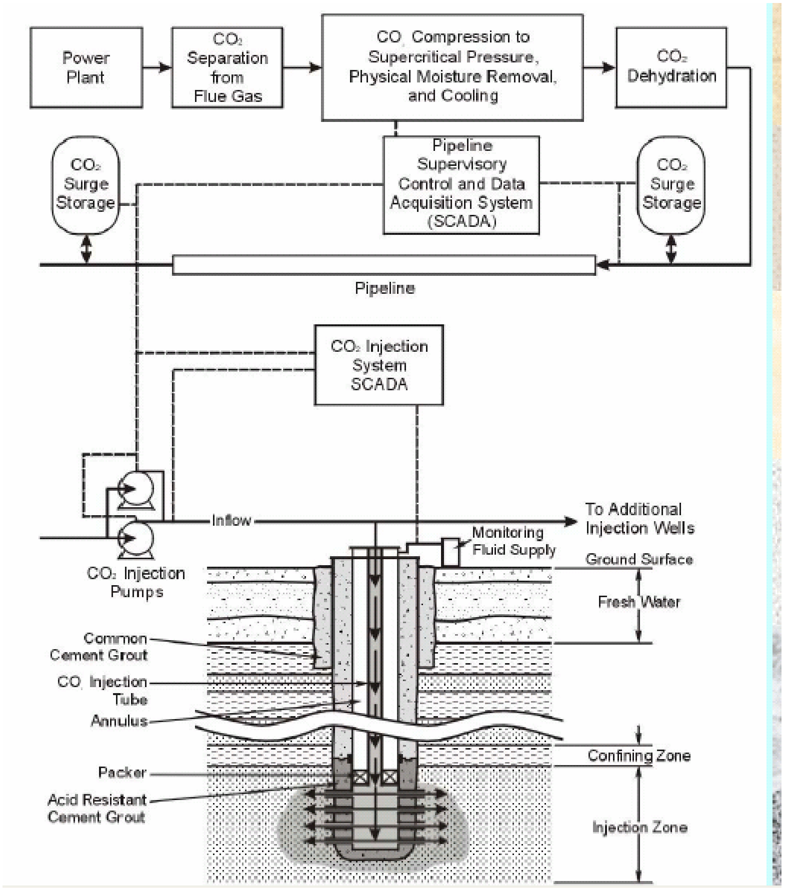
storage. In fact, reinjection of acid gas (a byproduct of oil and natural gas processing containing CO_2, hydrogen sulphide, and other byproducts) into depleted reservoirs has been practiced for many years, particularly in Canada. Acid gas often contains more than 90 percent CO_2, and oil and gas reservoirs have proven to be reliable containers of both acid gas and hydrocarbons.

Injection of CO_2 into oil reservoirs for EOR (CO_2-EOR) is a well proven technology. CO_2 mixes with otherwise irrecoverable oil and the mixture is extracted from the well. CO_2 upon separation from oil is reinjected back into the well. In many of these projects, however, the CO_2 is only temporarily stored in the well as blowing down (with water or air) is necessary to maximize oil recovery; only a small portion of injected CO_2 then remains dissolved in the oil residues in the reservoir. However, for long-term storage of CO_2 in the reservoir, as is the case with the Weyburn field in Canada, the injected CO_2 must not be blown down with air or water. CO_2-EOR is often referred to as a value-added CO_2 storage process as the resulting oil has a commercial value that offsets in full or part depending on the price of oil, the cost of separation, compression, transportation, and injection of the CO_2.[20]

Unmineable coal seams are considered another major potential storage site. CO_2 diffuses through coal and is physically adsorbed to it. The coal surface's affinity for CO_2 adsorption is higher than for methane. Thus CO_2 injected into these coal seams can enhance recovery of methane (ECBM). There could therefore be significant potential worldwide for ECBM if CO_2 storage in these unmineable coal formations is widely employed. ECBM is also a value-added activity as the methane recovered has a market value.[21] CO_2 -ECBM is in the early stages of field demonstration.[22]

Injection of CO_2 in deep subterranean and sub-seabed saline formations is considered the most likely storage option for two reasons: they are considered to have the largest storage potential and are widespread. Thus they are likely to be found in close proximity of CO_2 point sources. CO_2 is to be injected below 800 m (2600 feet) so that CO_2 remains in the supercritical dense phase. However at these depths CO_2 is lighter than brine and so will naturally rise to the surface. Geologic traps or impermeable cap-rock above the reservoir keep the CO_2 in the target host formation. Over time, CO_2 will dissolve in the formation waters and react with the minerals to form stable compounds and thereby become permanently trapped in the reservoir. (Refer to Figure 10 for a schematic diagram of a CCS-enabled power plant showing different system components.)

Research is currently underway to establish which deep saline formations would be suitable for long-term CO_2 containment. The two commercial scale projects of this type have been implemented at the Sleipner West gas field, 250 km off the coast of Norway, and at In-Salah, Algeria. CO_2, separated from natural gas, is compressed and injected into deep saline formations-sub-sea in the case of Sleipner, and in the water leg of the producing gas field in the case of In-Salah. The



Source: Battelle Memorial Institute.

Fig. 10. Carbon dioxide capture and storage-enabled power plant schematic diagram.

formations are being carefully monitored to identify any unexpected migration of the stored CO_2 or its release to the atmosphere to demonstrate that permanent storage of CO_2 in deep saline formations is a viable option. Each of these projects geologically stores more than a million tons of CO_2 per year; or to put it in context, six to seven such projects would be necessary to store the annual CO_2 emissions of a 1000 MW coal-fired power plant. Thanks to the Sleipner project, since 1996 about 3 percent of Norway's total annual CO_2 emissions have been stored in this aquifer. The project was made feasible by Norwegian government incentives as an offshore carbon tax credit. Statoil is planning another similar project in the Barents Sea off northern Norway.[23] The formations are being carefully monitored to identify interformation migration of the stored CO_2 or its release to the atmosphere.

ECONOMICS OF CCS

Fossil power plants represent the largest point sources of CO_2. CCS has therefore been primarily considered in the context of electricity generation

Research is underway to establish the suitability of particular deep saline formations for CO_2 containment.

TABLE 1
COST AND PERFORMANCE OF POWER PLANTS WITH CO_2 CAPTURE
(ADOPTED FROM RUBIN ET AL, 2004)**

Cost and Performance Measures	PC Plant Range low-high	PC Plant Rep. value	IGCC Plant Range low-high	IGCC Plant Rep. value	NGCC Plant Range low-high	NGCC Plant Rep. value
Emission rate w/o capture (kg CO_2/MWh)	722-941	795	682-846	757	344-364	358
Emission rate with capture (kg CO_2/MWh)	59-148	116	70-152	113	40-63	50
Percent CO_2 reduction per kWh (%)	80-93	85	81-91	85	83-88	87
Capital cost w/o capture ($/kW)	1100-1490	1260	1170-1590	1380	447-690	560
Capital cost with capture ($/kW)	1940-2580	2210	1410-2380	1880	820-2020	1190
Percent increase in capital cost (%)	67-87	77	19-66	36	37-190	110
COE w/o capture ($/MWh)	37-52	45	41-58	48	22-35	31
COE with capture ($/MWh)	64-87	77	54-81	65	32-58	46
Percent increase in COE w/capture (%)	61-84	73	20-55	35	32-69	48
Cost of CO_2 avoided ($/t CO_2)	42-55	47	13-37	26	35-74	47
Cost of CO_2 captured ($/t CO_2)	29-44	34	11-32	22	28-57	41
Energy penalty for capture (% MW_{ref})	22-29	27	12-20	16	14-16	15

*Definitions: MW_{ref} = reference plant net output; COE=cost of electricity; Rep. value=representative value; PC=pulverized coal; NGCC=natural gas combined cycle; IGCC=integrated gasification combined cycle. Notes: Ranges and representative values are based on recent studies reviewed (see text). Capture costs include compression. Cost of CO_2 avoided is based on the given plant type wit and without capture, but excluding transport and storage. NGCC cases based on natural gas prices averaging US$3/GJ. Coal prices average $1.3/GJ. Plant sizes range from 400-1200 MW (typical=550 MW).

**Rubin et al. (2004). Comparative assessments of Fossil Fuel Power Plants with CO_2 Capture and Storage. Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies. Vancouver, Canada. Sept. 5-9, 2004. Available at http://uregina.ca/ghgt7/PDF/papers/peer/475.pdf.

Cost comparisons tend to support the belief that CO_2 capture coupled with an IGCC plant will be cheaper than other options.

and a number of studies have been done to establish its impact on electricity prices.[24] CCS cost varies with the type of power plant, its efficiency, capacity factor, the method of CO_2 capture, the distance from the storage site, the terrain, and the depth of injection as well as the fuel price. The results of those studies apply to specific plants and storage options being considered (value-added or non-value-added) and are not easily generalizable.

Table 1 contains a summary of costs (ranges) for three types of power plants—pulverized coal (PC), Integrated Gasification Combined Cycle (IGCC), and Natural Gas Combined Cycle (NGCC). The power plants are assumed to be new and the costs of capturing CO_2 include the cost of compression but not transportation and storage. Transportation and storage costs[25] depend on the storage option used (e.g., EOR or non-value-added storage) and are fairly generic across technologies and, therefore, the capture costs (using the same capture method) essentially demonstrate the relative costs for each power generation technology, all else being equal.

The costs for avoided and captured CO_2 given in the table tend to support the widely held belief that CO_2 capture coupled with an IGCC will be cheaper than other CCS-enabled power production options in many locales and under most circumstances. There is some overlap in the costs of electricity, with the CCS-enabled NGCC option appearing most cost-effective. It should be noted, however, that the estimated costs are highly sensitive to the plant utilization, loading, and fuel price assumptions.

The pipeline transportation cost based on a quantity of 10 million metric tonnes per year (equal to the emissions of a 1500 MW PC plant) is in the order of $0.50/metric tonne/100 km. Truck transport of liquefied CO_2 is in the order of $6.00/metric tonne/100 km. The typical storage cost consisting of transport and injection, based on a distance of approximately 200 miles between the source and the sink, is in the range of $3 to 5.50 per metric tonne of CO_2 ($11-20 per metric tonne carbon); however, if CO_2 is used for enhanced oil or gas recovery then a byproduct credit will be available that will offset the storage costs, in part or in full depending on the commodity price.[26]

According to some estimates, with today's level of technology for CCS to be widely adopted by the power industry, carbon prices (established through tax, a cap-and-trade system, or some other regulatory means) will have to reach $100/tC over a significant fraction of the assets' lifetime to make the application of CCS technologies an economic choice.[27]

REGULATORY ISSUES OF CAPTURE AND GEOLOGIC STORAGE OF CO_2

In the case of CCS, several regulatory problems might fall under the state public service commission's direct purview. These could include: pipeline safety, rights of way, and underground injection and storage.

Pipeline Safety

The DOT has authority over the safety and environmental effects of pipeline transmission. Within the DOT, the Office of Pipeline Safety (OPS) regulates the interstate transportation of CO_2 via pipeline. The OPS certifies state agencies to inspect and enforce the regulations for intrastate pipelines. For many states, the state agency with jurisdiction is the public utility or public service commission. States must enforce federal regulations, but they are free to supplement these with state-specific regulations provided they are consistent with the federal standards. The state agencies are partially funded (up to 50 percent) by OPS.[28]

Although CO_2 is not considered to be hazardous, pipelines transporting CO_2—defined as a fluid consisting of greater than 90 percent CO_2 molecules compressed to a supercritical state—are regulated under the same scheme as hazardous liquid pipelines.[29] The federal regulations include provisions for safety in the design, construction, inspection, operation, and monitoring of pipelines.

Among other requirements, all new pipelines must have a competent dielectric coating to prevent corrosion and must have a cathodic protection system. This system should be regularly monitored to ensure the electric current levels are sufficient and that no corrosion is occurring. With CO_2 pipelines, a primary concern is the formation of carbonic acid in the presence of water. Thus, water in the pipeline must be kept to a very low percent. The OPS has authority to carry

If today's level of technology for CCS is to be widely adopted by the power industry, carbon prices will have to substantially increase through a tax, cap-and-trade credits, or some other regulatory means.

Although CO_2 is not considered hazardous, pipelines transporting it are regulated under the same scheme as hazardous liquid pipelines.

The existing CO_2 pipeline network is small but growing.

Siting a pipeline may take many years. But many coal-fired electric power plants would require only short pipelines.

Rights-of-way will be an important issue if pipelines are not entirely located on one company's land.

out audits and inspections to ensure compliance.

The existing CO_2 pipeline network is small when compared to oil or natural gas pipelines, but has been growing for the last 20 years. So far, the infrastructure in the United States has developed in the West for transporting CO_2 from natural underground sources to EOR operations. Based on this experience, it is reasonable to conclude that CO_2 pipelines can be regulated by existing institutions.

Natural gas regulation also provides an analogue. The Natural Gas Pipeline Safety Act provides for federal regulation of interstate transportation and storage of natural gas.[30] State governments may regulate intrastate pipelines as long as the state regulations do not conflict with the federal minimum standards. Liability for accidents is determined by common law principles. Because the benefits of natural gas are deemed to offset the risks, the operation of natural gas pipelines is not considered ultrahazardous, and negligence is the standard of care.[31] Without specific statutory standards for liability, CO_2 might be treated under the common law in a similar manner.

Other surface risks are covered by state environmental health and safety regulations (EHS). EHS regulations are established by the Occupational Health and Safety Administration and the Department of Labor, and adopted and enforced mainly by the states. Agencies within the Department of Health and Human Services also set recommended exposure limits for humans.

Rights-of-Way

Siting a pipeline entails obtaining the proper regulatory permits and acquiring use of the land that the pipeline will occupy. Depending on the location of the proposed pipeline, environmental impact assessments, permitting and acquisition of rights-of-way can take several years. After a pipeline route has been approved, land along the route must be acquired by an easement agreement, by purchase or via eminent domain.

Nonetheless, the close proximity of many coal-fired electric power plants—currently the largest CO_2 emitters—and deep saline formations or other suitable geologic formations, particularly in the Midwest region, mean that many projects will require only short pipelines. Some of these pipelines may be entirely located on one company's land. In such cases, rights-of-way will not be an issue. Where longer pipelines are needed, one of the key issues in the regulation of CO_2 pipelines will be whether the power of eminent domain can be used to secure rights-of-way.

A right-of-way agreement between the pipeline company and a landowner is a form of easement. An easement does not grant an unlimited entitlement to use the right-of-way. The rights of the easement owner (pipeline company) are set out in the easement agreement. Like contracts, the terms of the easement agreement control the rights and obligations of the parties *inter se*.

When the terms are ambiguous or the agreement is silent on an issue, general legal principles govern. In interpreting an easement, the intentions of the parties at the time of the grant are taken into account. Generally, use of an easement is limited to what is reasonably necessary to carry out the intended purpose. These issues become important when pipelines must be constructed in existing right-of-way corridors where the easements may be many decades old. Some questions that will need to be asked are:

(1) Does the original easement grant the right to install and operate CO_2 pipelines?[32]
(2) How much, if anything, does each landowner or easement holder need to be compensated for the use of the easement?
(3) Can existing easements be sold or leased to third parties?

Many of these issues have recently been addressed with the installation of fiber optic lines in existing utility right-of-way corridors. Fiber optic lines are analogous to CO_2 pipelines in that they are both relatively new technologies that would not have been explicitly included in older easements. The cases that resulted from placing fiber optic lines in existing utility rights-of-way demonstrate a wide range of variation in both the language of the original easements and the interpretation of this language by the courts.

If the legislature and/or state commission concluded that CCS would be in the public interest, an issue for transportation of CO_2 via pipeline is whether current state condemnation statutes and regulations allow for treating CO_2 pipelines as a public utility or a common carrier. The Federal Energy Regulatory Commission (FERC) has broad authority over interstate pipeline matters. For natural gas pipelines, FERC has jurisdiction over tariffs and rights-of-way.[33] As of January 2006, FERC had not asserted jurisdiction over CO_2 pipelines. Moreover, it is unclear whether FERC could assert jurisdiction in the absence of specific legislative authority.

In much of the West, the Bureau of Land Management (BLM) administers land. Therefore for the West, it is useful to briefly examine the basic right-of-way provisions of the Forest Land Policy and Management Act (FLPMA) and the Mineral Leasing Act (MLA).[34] The right-of-way sections of the FLPMA and the MLA are similar. One of the differences will be important in determining which statute applies to pipelines involved with geologic CO_2 storage, however. The MLA imposes a common carrier requirement; the FLPMA does not. Recent BLM practice has been to consider CO_2 as a "natural" gas. This has resulted in legal challenges by companies that do not want to be bound by common carrier requirements. A common carrier requirement allows other companies transporting CO_2 to utilize the pipelines.

Although the BLM permits existing CO_2 pipelines under the MLA, and therefore imposes a common carrier requirement, it is not clear that pipelines associated with geologic CO_2 storage would have a common carrier requirement. This is because the com-

Many rights-of-way issues have recently been addressed with installation of fiber optic lines in existing utility corridors.

Is a CO_2 pipeline a public utility or common carrier. So far FERC has not asserted jurisdiction, and it is not clear it can without legislation.

In the West, the BLM might consider CO_2 a waste rather than a consumer product, making a common carrier provision unnecessary for CO_2 pipelines through federal lands.

mon carrier requirement of the MLA appears to be aimed at protecting consumers. The common carrier section of the MLA exempts public utilities under the jurisdiction of state public utility commissions that regulate the rates charged for natural gas to consumers.[35]

Given that CO_2 destined for geologic storage might be considered a waste rather than a consumer product, the BLM and other relevant agencies may determine that a common carrier provision is not necessary. In the case of the BLM, that would mean deciding that CO_2 destined for geologic storage is not a natural gas or a refined product of a natural gas. The BLM could then issue pipeline right-of-way permits for CO_2 destined for geologic storage under the FLPMA instead of the MLA. BLM right-of-ways will not be important in other regions. Nonetheless, similar issues relating to the classification of CO_2 pipelines will arise in states.

One-Stop Siting Agency

A one-stop siting agency would facilitate CCS.

A one-stop siting agency, similar to the Ohio Power Siting Board, would greatly facilitate all phases of CCS as well as other energy facilities. Best practices for a siting agency include:[36]

- A broad jurisdictional scope that encompasses all stages of CCS, including electric generation and CO_2 capture, selection of the geologic storage site, transportation, injection, and monitoring
- A comprehensive process that incorporates all state and local permitting agencies, with a continuing long-term coordination of agencies with oversight responsibility
- Clear standards for review
- Preliminary site studies to facilitate better planning
- Public participation beginning early in the siting process
- Formal legal proceedings with the right of judicial review
- Statutory power of eminent domain

Underground Injection

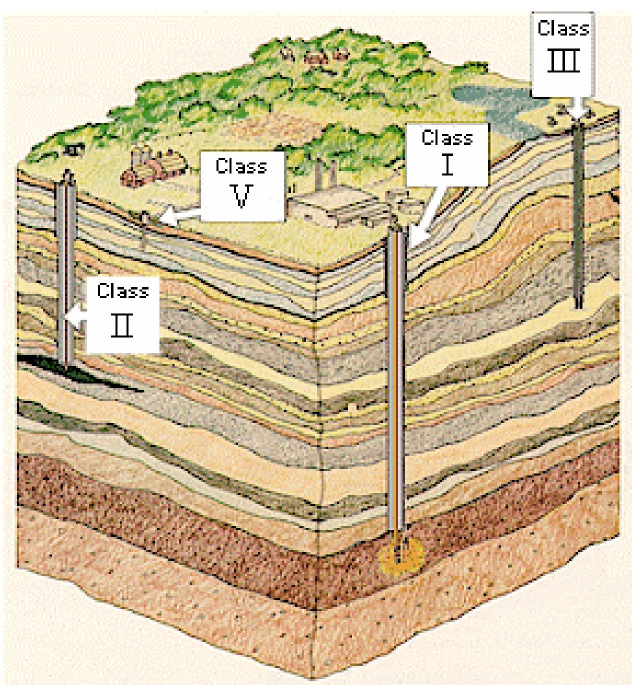
The Underground Injection Control Program (UIC), administered by the U.S. Environmental Protection Agency (EPA), regulates underground injection of wastes and other fluids. The UIC regulations were enacted pursuant to the Safe Drinking Water Act (SDWA).[37] The UIC Program has several decades experience regulating underground injection wells.

The use of CO_2-EOR projects is licensed under the joint federal-state UIC programs. In some states, it is the state public service commission that administers this joint program. The most important difference between many existing EOR operations and some of the proposed geologic CO_2 storage projects is that the EOR operations are not meant for the long-term isolation of CO_2 from the atmosphere as a means for addressing climate change concerns. Current EOR regulations do not address issues related to the retention of CO_2 in the geologic containments: monitoring of interformation migration of CO_2 or leakage to the atmosphere and verification of the quantities involved.

At present, CO_2 used in EOR is treated as a commodity, and state public utility commissions or gas and oil commissions have jurisdiction. The Interstate Oil and Gas Compact Commission (IOGCC) recommends that all CO_2 which is stored in deep geologic formations for the purpose of addressing climate change should also be treated as a commodity.[38] Geologic storage of CO_2 might be distinguished from that used in EOR however. The geologic storage plans for the future do not necessarily contemplate further use of the CO_2. Therefore, others argue that it should be treated as a disposed waste, rather than a stored commodity. If this occurs, regulatory jurisdiction over geologic CO_2 storage might be more contentious. There are no existing regulations covering long-term storage of CO_2. If in the future sequestered CO_2 is treated as a waste, then state natural resource departments or environmental agencies might have regulatory authority. Given the status quo, the only regulatory framework that will clearly have jurisdiction over geologic CO_2 storage is the UIC program.

A crucial question under this scheme is how CO_2 and storage wells would be classified. As illustrated in Figure 11, under the UIC system, there are five classes of wells based primarily on the type and depth of injection. These are defined in 40 CFR 144.6. The UIC regulations establish specific criteria for the construction, operation and monitoring of injection wells. The permitting process for UIC

At present, CO_2 used in EOR is treated as a commodity, and state public utility commissions or gas and oil commissions have jurisdiction.



Source: U. S. Environmental Protection Agency.

Fig. 11. Underground injection well classes.

Given the status quo, the only regulatory framework that will clearly have jurisdiction over geologic CO_2 storage is the UIC of the EPA. The UIC framework has five well classifications.

CO_2 is not listed as a hazardous waste by the EPA, nor is it particularly ignitable, corrosive, reactive, or toxic.

wells consists of providing the information listed in 40 CFR 146 or applicable state regulations to the UIC director with jurisdiction over the well site. The information required relates to geological considerations, structure of the well, operational considerations, status of other wells in the area and the proposed monitoring of the operation. After submission of the application, a draft permit decision will be prepared and published for notice and comment. Any person may request a public hearing for further comment.[39]

Class 1 wells are those used for deep injection of hazardous and nonhazardous industrial or municipal liquid wastes below the lowest sources of potable groundwater within one quarter mile of the wellbore. When not administered directly by the federal EPA, Class 1 wells are normally regulated by state agencies of environmental protection or natural resources.

Class 2 wells inject fluids for disposal that are associated with oil, gas, or natural gas production and methane gas dehydration. Class 2 also covers wells used for enhanced recovery of oil and gas. This category includes wells used to dispose of fluids employed in EOR and fluid hydrocarbons. The most common Class 2 wells are those disposing of brine water brought to the surface with hydrocarbons, enhanced hydrocarbon recovery wells, and liquid hydrocarbon storage. Offsite waste fluids are not defined as oil field fluids and, under existing regulations, cannot be disposed of in a Class 2 well.

Class 3 wells are used for injecting materials associated with *in situ* mineral extraction, mostly uranium or salt.

Class 4 wells are those used for hazardous or radioactive waste injection. These are generally prohibited.

Class 5 includes wells that do not fit into the first four categories. These are predominantly shallow injection wells. Experimental research wells also tend to be put into Class 5 as well.

Another issue under the UIC framework is whether or not CO_2 should be considered hazardous or nonhazardous.[40] This is important because, among other reasons, in ten states, including Ohio and Michigan, a 10,000 year no-migration demonstration is required for Class 1 hazardous waste wells. The SDWA definition is the same as that of the Resource Conservation and Recovery Act. The EPA's definition of hazardous waste is found in 40 CFR 261. Certain wastes are listed as hazardous in 40 CFR 261(D); others are hazardous because they have one of four hazardous characteristics (ignitable, corrosive, reactive, or toxic). CO_2 is neither listed as a hazardous waste nor is it particularly ignitable, corrosive, reactive, or toxic. Therefore, CO_2 might be considered non-hazardous. Moreover, there appears to be a growing view among the regulators working in the UIC program and those in the oil and gas field that CO_2 should be considered nonhazardous, with some contending it should be treated possibly as a nonhazardous industrial waste.

Geologic CO_2 storage is a new endeavor. As such the long-term consequences of geological CO_2 storage are not known. Consequently, more detailed geologic and hydrologic data and modeling must be done before further classifying CO_2 injection wells. For many regulators of underground injection wells, UIC Class 1 (non-hazardous) or Class 5 appear to be the most appropriate classification.

Others make the case that Class 2 might be more suitable. This argument is based on the fact that the costs and delays that might accompany Class 1 permitting could discourage some CCS projects. Because Class 1 wells face more stringent regulations, the permitting process costs more and takes longer than Class 2 wells. Considering the costs of preparing a petition and geologic modeling and testing, a petition could cost more than \$2,000,000.[41] However, many of the requirements are the same for both Class 1 and Class 2 wells. Both need a permit unless authorized by rule.

Rather than putting CO_2 injection into one of the existing UIC classes, there is also the possibility of creating a sixth class specifically designed for geologic CO_2 storage. According to some regulators, the new regulations could be enacted within five years. Any wells put into operation in the interim could be regulated under the existing UIC program. Whether or not a new class of UIC wells is developed will depend on the expansion of geologic CO_2 storage and concomitant policy considerations.

Another proposal has been put forth by the IOGCC that advocates regulating geologic CO_2 storage as either UIC Class 2 or under state natural gas storage statutes.

Consol Energy has a project with five test wells in West Virginia. Injection of CO_2 is still several years away, therefore the company has not yet applied for a permit. The West Virginia Division of Environmental Protection, Division of Water Resources, Groundwater Program will most likely require a Class 5 permit for the injection wells.[42]

The recent Frio pilot project (injection into a brine-bearing interval) in Texas by the University of Texas received a Class 5 permit. Class 5 was chosen rather than Class 1 because: (1) the injection period was brief; (2) the amount of CO_2 was small (3000 tons); (3) the food-grade CO_2 injected is considered a benign substance; (4) as an experiment it will be closely monitored; (5) the injection area is not suitable for Class 1 wells due to faults and heavy drilling for oil wells; and (6) the permitting process is faster for Class 5, so information that will benefit future projects can be gathered quickly.[43] Unlike EOR wells, hydrocarbon production is not part of the research project. Therefore, a Class 2 permit was not applied for.

Despite the comprehensive regulatory scheme developed for the UIC program, a possible gap exists in regard to geologic storage of CO_2. Specifically, there is no federal requirement for monitoring the actual movement of fluids or gas within the injection zone;

More detailed geological hydrologic data and modeling must be done before further classifying CO_2 injection wells.

A possible regulatory gap is the lack of a federal requirement for monitoring the actual movement of fluid or gas within the injection zone or monitoring for leakage.

nor are there requirements for monitoring in overlying layers to detect leakage.[44] Given the long time frame for geologic CO_2 storage, monitoring for migration might be required. Also, financial responsibility for long time frames might be necessary. Requiring geologic CO_2 storage projects to obtain a Class 1 UIC permit might help to ensure that there is an adequate plan for after the well is closed that includes continued monitoring and financial responsibility. The specific characteristics, especially the long time frame, of geologic CO_2 storage need to be fully considered before large-scale commercial projects begin.

The specific characteristics of storage, especially the long time frame, need to be fully considered before large-scale commercial projects begin.

The current UIC regulatory scheme will likely be extended to cover geologic CO_2 storage, unless other regulations are developed. EPA Regional Offices and state offices are regulating the injection at current demonstration projects as Class 5 experimental wells.

Surface and subsurface property rights will affect CO_2 storage.

As with oil and natural gas, surface and subsurface property rights will affect the regulation of CCS, the cost of transportation and storage of CO_2, and will be central in determining liability. Property rights issues that might affect CCS operations include, among other things: surface rights and easements, subsurface mineral rights, ownership of the injected CO_2, neighboring mineral leases, and water rights. Property rights also affect issues of liability. Because property rights are governed by state law and often develop through state court precedent, it is difficult to predict precisely how property issues will affect CCS.[45] Nonetheless, the basic issues that might arise can be anticipated.

In regard to owners of injected CO_2, potential conflicts could arise with surface estate owners. If injected CO_2 migrates laterally beyond the reservoir where property rights have already been secured, the adjacent surface estate owners may have legal causes of action such as trespass,[46] nuisance,[47] negligence, strict liability, or unjust enrichment.

Under the surface, similar concerns must be addressed with owners of mineral estates and water rights. Most issues involving water resources will be taken care of by the permitting process if the UIC program governs geologic CO_2 storage. Subsurface mineral rights will be determined by state laws. The rules for mineral rights developed primarily from oil and gas law. Some of these rules might not apply, or might require some modification to apply to geologic CO_2 storage.

In summary, the regulatory issues of CCS are complex, requiring interagency coordination to smoothly deal with transportation issues, such as pipeline safety and rights of way, as well as injection and storage issues. State public utility commissions can play a key role in encouraging interagency coordination on the regulatory issues of CCS, as well as cost recovery.

State public utility commissions can play a key role in encouraging interagency coordination on the regulatory issues of CCS, as well as on cost recovery.

TERRESTRIAL SEQUESTRATION

Terrestrial carbon sequestration includes both the net removal of CO_2 from the atmosphere and the prevention of CO_2 net emissions from the terrestrial ecosystems into the atmosphere. Net removal of CO_2 from the air entails transferring of CO_2 into soils and vegetation (long-lived carbon pools) through natural processes of photosynthesis, humification, aggregation, and calcification. It is important to note that sequestration requires that carbon must be fixed into long-lived carbon pools (e.g., standing biomass such as trees or in root mass and inorganic carbon compounds in the soil) and remain there for a significant period of time (decades at least) for terrestrial sequestration to be a viable means of addressing climate change.

Scientists estimate that improved land use practices that enhance carbon storage in soil could sequester 5 to 15 percent of anthropogenic CO_2 globally.[48] Two approaches to enhancing the carbon sequestration potential of soil are: (1) protection of ecosystems that store carbon in order to maintain or increase sequestration; e.g., efforts to stop deforestation in developing nations and elsewhere in the world; and (2) manipulation of ecosystems to increase their ability to sequester carbon.

Forests and agricultural soils store carbon. Research indicates that erosion control and no-till or low-till cropping reduces the amount of CO_2 released into the atmosphere. Tilling soil exposes carbon in the soil to air, thereby oxidizing it and releasing CO_2 into the atmosphere. Tilling also increased the rate of soil erosion. Trees store carbon in their cells. This carbon is released as CO_2 into the atmosphere when the trees die and decompose. Soil is also a repository for decaying plants; returning crop residues to soil also enhances carbon storage. Other methods include: growing plants that have large capacity to store carbon in above-ground or below ground biomass, reforestation, and improved methods of logging to minimize forest disturbance.

REGULATORY ISSUES OF TERRESTRIAL SEQUESTRATION

There are fewer regulatory barriers to implement terrestrial sequestration projects. However, verification of the amount of CO_2 sequestered and permanency can be thorny issues, requiring special monitoring, especially as carbon markets develop to trade fungible carbon credits. Regulators may find it helpful to become familiar with the regulatory aspects of both geological and terrestrial sequestration, as they can affect cost recovery of electric utilities.

To date, terrestrial sequestration has primarily been carried out under private contract with farmers, foresters, and others. The carbon sequestered is then traded on the Chicago Climate Exchange. There is no direct regulation of such contracts. Due to the public interest of the subject matter, however, there is indirect regulation of private contracts. A major area of concern is monitoring and verification. Agriculture is considered a non-point source of pollution. Carbon released from terrestrial sources is much more difficult to monitor than a point source such as a power plant. As a consequence, Entergy's private contracts provide that the third parties shall have access to the fields.[49]

Terrestrial carbon sequestration includes net removal of CO_2 from the atmosphere and prevention of net emissions from the terrestrial ecosystems into the atmosphere.

Verification of the amount of CO_2 sequestered and the permanency of storage can be thorny issues.

Some regulatory issues will involve how to encourage land and forest use that captures and stores carbon.

Apart from capture and geologic storage or terrestrial sequestration of CO_2, a number of alternative approaches have been proposed.

The ocean is the largest potential sink for manmade CO_2.

The farmers are also responsible for self-reporting in writing to their local conservation districts. The conservation districts are quasi-governmental agencies working with the U.S. Natural Resources Conservation Service to develop and monitor projects funded by the U.S. Department of Agriculture (USDA). Estimates for the amount of carbon sequestered are based on local soil samples and the USDA's CQESTR model.[50] Once carbon markets are well established, there will be a need for trusted third party verification and monitoring. As demonstrated in the above example, using the existing regulatory institutions is a logical place to start.

Although terrestrial sequestration remains largely private, there is a public interest in encouraging sequestration and monitoring sequestration projects. Thus there will be a role for regulation. Some regulatory issues will involve how to encourage land and forest use that sequesters carbon and discourage practices that release carbon. Regulations could restrict land use practices and require replanting of harvested forests (for example, via conservation easements), provide for subsidies and taxes, and/or stipulate how property rights in sequestered carbon are obtained and transferred. More generally, regulations could require CO_2 emitters to offset emissions in sequestration projects. Oregon has done this, and gone a step further. The Oregon Office of Energy's Energy Facility Siting Council considers emissions offset projects before issuing a site certificate for the construction of new electric power plants.[51]

OTHER CARBON SEQUESTRATION OPTIONS AND CONCEPTS[52]

Apart from capture and geologic storage of CO_2 and terrestrial sequestration, a number of alternative approaches for capture and storage have been proposed. Given below is a cursory description of some of those proposed alternatives that are receiving increasing attention.

A possible storage site for CO_2 is the ocean. The ocean represents the largest potential sink for manmade CO_2. Deep ocean water is unsaturated with respect to CO_2. If liquid CO_2 is discharged below 3,000 meters where CO_2 is denser than seawater, it descends to greater depths, forming a deep lake. If liquid CO_2 is discharged at depths of 1,500-3,000 meters through a diffuser such that the liquid breaks up into droplets, then CO_2 dissolves completely before it rises 100 meters. Both of these methods however are controversial because they would increase the acidity of seawater. A third method is to bring seawater in contact with CO_2, such as the flue gas at a power plant, and then treat the CO_2-rich water with carbonate minerals to form soluble bicarbonates before discharging back into the ocean. The advantage of this method is that sea water would not be acidified. Ocean sequestration results in the formation of carbonates and bicarbonates which are natural ingredients of sea water; however, many questions remain unanswered regarding the long-term consequences of carbon sequestration on the marine eco-system and thus the proposal remains controversial. Some very limited experimentation has been carried out.

It has also been shown that fertilizing the ocean with nutrients such as iron dramatically enhances the growth of phytoplankton biomass and thereby uptake of atmospheric CO_2 by the ocean is increased. The presumption is that a portion of this phytoplankton will eventually sink to the deep ocean. Using this method the cost of carbon sequestration has been estimated to be in the order of $1-10/tC. However, there are many significant concerns about the effects of this intervention on the ecosystem that cannot be directly measured or factored into cost-benefit calculations, such as oxygen depletion and changes in the phytoplankton communities.

Another concept is to grow microalgae in artificial ponds fertilized with CO_2 from flue gas. The growth of microalgae under these conditions is likely to be enhanced. This algal biomass can be converted to food, feed or fuel. Food or feed upon digestion will return CO_2 and other greenhouse gases to the atmosphere; however, use of bio fuel to replace fossil fuel will eliminate the fossil fuel generated CO_2. The method is not cost effective at this point in time.

Another proposed method is mineral carbonation or fixation of CO_2 in the form of inorganic carbonates. There are some minerals found on earth (e.g., serpentine, a silicate of magnesium) that naturally uptake CO_2 from the atmosphere to form carbonates, thereby permanently locking carbon. This natural process is, however, very slow. Research continues to identify pathways that would accelerate this reaction. For example, reactions of CO_2 with metal oxide-bearing materials have been conducted to produce corresponding metal carbonates and a solid byproduct such as silica, but this requires energy intensive preparation of the solid reactants and thus translates into a high energy penalty on the original power plant. The method is attractive in that the magnesium and calcium silicate deposits on earth are sufficient to store on a geological time scale all the CO_2 that would be produced from the combustion of all fossil fuel resources and, also, the carbonation reaction is exothermic and therefore, theoretically, can yield energy. A full CCS option, using the best available carbonation technology today, would require 60-180 percent more energy than a power plant with similar output but without CCS.[53]

POLICY ISSUES ON THE HORIZON

Geologic CO_2 storage and terrestrial carbon sequestration is a topic that will likely involve state public service commissions, state and federal environmental agencies, state departments of natural resources, and the DOT, to name a few. Planned field tests to be conducted over the next four years under the DOE's Carbon Sequestration Program are bringing to the fore issues related to the regulation of CCS and terrestrial carbon sequestration. Regulatory issues associated with CCS, particularly geologic CO_2 storage, can be complicated, requiring interagency coordination. The benefit of this early coordination is likely

All of the options for ocean storage have serious potential drawbacks.

Use of microalgae instead of fossil fuel is not a cost effective alternative today.

The natural process of mineral carbonation is too slow and would itself use considerable energy.

Planned field tests under the DOE's Carbon Sequestration Program are bringing CCS, particularly geological CO_2 storage, to the fore.

State commissions are positioned to play a key role in implementation.

most apparent for applications of CO_2 capture technologies with geologic CO_2 storage, given the long-lived and capital intensive nature of these assets; e.g., a CCS-enabled power plant and the associated CO_2 transport and injection infrastructure.

CCS is a relatively new concept and requires infrastructure and technologies that are new to the marketplace. Much work will need to be accomplished by the regulators and the parties involved to ensure that the siting process is safe and reliable, that accurate monitoring and verification protocols to ensure storage efficacy are in place, and that project noncompliance has a downside for the emitter. In addition, trading of carbon "credits" will likely require greater oversight in the future to ensure that one credit traded equals one unit of carbon sequestered or otherwise not emitted.

Although the topics of geologic CO_2 storage and terrestrial carbon sequestration might at first glance seem principally of primary concern of environmental regulators, in fact state public utility regulators are positioned to play a key role in implementation. The state commission's major role of cost recovery is, of course, critical for the implementation of these seemingly promising climate-change mitigation technologies. In addition, many state commissions will regulate pipeline safety, siting (including rights-of-way and condemnation), and, for some commissions, underground well injection policy. Commissioners in states with fossil-burning electricity generation plants (particularly older, coal-fired units) may wish to gear up on these issues and be prepared to engage in interagency coordination as CCS pilot projects will be shortly undertaken through DOE-sponsored Regional Carbon Sequestration Partnerships, such as the Midwest Regional Carbon Sequestration Partnership.

Notes

[1] Carbon Sequestration Leadership Forum available at http://www.cslforum.org/education.htm.

[2] For more information on Regional Carbon Sequestration Partnership visit http://www.netl.doe.gov/technologies/carbon_seq/partnerships/partnerships.html.

[3] For more information on the Midwest Regional carbon Sequestration Partnership visit http://www.mrcsp.org.

[4] The U.S. Environmental Protection Agency (EPA) available at http://yosemite.epa.gov/oar/globalwarming.nsf/content/climate.html.

[5] Available at http://yosemite.epa.gov/OAR/globalwarming.nsf/UniqueKeyLookup/SHSU5BUM9T/$File/ghg_gwp.pdf.

[6] There are some differences in viewpoint, however, among scientists about the effects of climate change (see, for example, http://www.npr.org/templates/story/story.php?storyId=1893089 and http://www.loe.org/pdfs/050624debate.pdf). Most scientists consider that emission of greenhouse gases at current levels due to human activities will bring about a detrimental change in the earth's climate although the magnitude and significance of the effects are not fully resolved, and now the attention seems to be turning to how do we address the issue. (See, also, Dan Vergano (USA Today June 13, 2005: A.1). The debate's over: Globe is warming).

[7] Molecules of greenhouse gases absorb different amounts of heat. For the ease of comparison, all emissions are converted to equivalent CO_2 emissions; e.g., a molecule of methane traps 21 times more heat than a molecule of CO_2. A list of greenhouse gases with their corresponding global warming potentials is available from the U.S. Climate Change Technology Program available at http://www.climatetechnology.gov/library/2003/currentactivities/othergases.htm.

[8] EPA. U.S. Emissions Inventory 2005. Available at http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2005.html.

[9] For a detailed discussion visit the website on Global Warming maintained by the EPA available at http://yosemite.epa.gov/oar/globalwarming.nsf/content/climate.html and http://yosemite.epa.gov/oar/globalwarming.nsf/content/ClimateUncertainties.html.

[10] Ibid.

[11] Department of Energy (DOE) (2005). Emissions of Greenhouse Gases in the United States 2004. Energy Information Administration: Office of Integrated Analysis and Forecasting. Available at ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/pdf/ggrpt/057304.pdf.

[12] For more information refer to the website maintained by the DOE on Greenhouse Gas Facts available at http://www.netl.doe.gov/publications/carbon_seq/ghgfacts.html.

[13] Information on enhanced oil recovery methods is available at the National Energy Technology Laboratory (NETL) website entitled Oil and Natural Gas Supply-Exploration and Production Technologies. Available at http://www.netl.doe.gov/technologies/oil-gas/E%26P_Technologies/E%26P_main.html.

[14] NETL (2005). Presentation by Scott Klara on the DOE Carbon Sequestration Program. 2005 Annual Sequestration Conference, Alexandria, VA: May 2-4, 2005. Available at http://www.netl.doe.gov/publications/carbon_seq/05Klarantlconference.pdf also see DOE Techlines News available at http://www.fossil.energy.gov/news/techlines/index.html. Release dated Nov. 17, 2005 entitled DOE Advances Oxycombustion for Carbon Management.

[15] A somewhat similar scheme has been proposed as part of Japan's Hydrogen fired power plant program. See, for example, Shoichi, H. et. al. A Vision for Thermal Power-Plant Technology Development in Japan. Tokyo: Toshiba Corporation. Available at http://www.worldenergy.org/wec-geis/publications/default/tech_papers/17th_congress/4_1_05.asp#Heading10.

[16] Stelter, S. (2001). The New Synfuels Energy Pioneers. Bismark: Dakota Gasification Company.

[17] Intergovernmental Panel Climate Change (IPCC) (2005). IPCC Special Report on Carbon dioxide Capture and Storage. Final Draft. October: Chapter 4.

[18] Battelle (2001). Carbon Dioxide Sequestration in Saline Formations(Economic and Engineering Assessment. Battelle Project: DE-AC26-98FT40418, MOD 006. (The lower pressure limit is set to ensure that pipeline operation does not enter the two-phase region.)

[19] IPCC (2005). IPCC Special Report on Carbon dioxide Capture and Storage. Final Draft. October: Appendix I.

[20] Wellington, S. et al. (2005). New Opportunities for Gasification. San Francisco, CA: GCG Conference. Available at http://www.gasification.org/Docs/2005_Papers/19WELL.pdf.

[21] Bromhal, G. et al. (2004). Assessing Economics for Sequestering Carbon Dioxide (CO_2) in Coal Seams with Horizontal Wells. Alexandria, VA: 3rd Annual Sequestration Conference.

[22] Reeves, S. (2003). Geologic Sequestration of CO_2 in Deep, Unmineable Coalbeds: An Integrated Research and Commercial-Scale Field Demonstration Project. Tuscaloosa, AL: International Coalbed Methane Symposium. Available at http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/3a1.pdf.

[23] More information on current and planned research projects is available from the IEA Greenhouse Gas Research and Development Program available at http://www.co2captureandstorage.info/.

[24] Rubin et al. (2004) available at http://uregina.ca/ghgt7/PDF/papers/peer/475.pdf. Comparative assessments of Fossil Fuel Power Plants with CO_2 Capture and Storage. Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies. Vancouver, Canada. Sept. 5-9, 2004.

[25] For estimates of storage costs associated with different geologic and ocean storage options see, Heddle et al. (2003). The Economics of CO_2 Storage. MIT LFFE 2003-003 RP. Cambridge, MA: Massachusetts Institute of Technology. Available at http://sequestration.mit.edu/pdf/LFEE_2003-003_RP.pdf.

[26] Herzog, H. et al. (2004). Carbon Capture and Storage from Fossil Fuel Use, in C.J. Cleveland (ed.), Encyclopedia of Energy, Elsevier Science Inc., New York, pp 277-287, (2004). Available at http://sequestration.mit.edu/pdf/enclyclopedia_of_energy_article.pdf.

[27] Herzog, H. (2004). CO_2 Capture and Storage: Costs and Market Potential. GHGT-7.

[28] See 49 U.S.C. §60105(a).

[29] 49 CFR 195 Transportation of Hazardous Liquids by Pipeline has been revised to include the transportation of carbon dioxide. CO_2 is not, however, considered hazardous.

[30] 49 U.S.C. §1671 et seq.

[31] See e.g., Moore v. Sharp Gas, (C.A. Nos. 90-504 MMS, Dist. of Delaware 1992 LEXIS 9380).

[32] A wide variety of phrases are used in easements, from grants permitting a "natural gas pipeline" to "pipelines for the transportation of oil, hydrocarbons, gas, water, and any other substances whether fluid or solid, any products and derivatives of any of the foregoing, and any combination and mixtures of any of the foregoing..." While there is a tenable argument that CO_2 pipelines should not be covered by the former, it would be much harder to make such an argument for the latter.

[33] FERC's jurisdiction is based on the Natural Gas Act, the Natural Gas Policy Act of 1978, and 18 CFR 284.

[34] Mineral Leasing Act, 30 U.S.C. 185 (1988).

[35] 30 U.S.C. §185(r)(3)(A).

[36] States might also consider financial incentives to decrease carbon dioxide emissions. State siting agencies might play a role in facilitating incentive programs as well as permitting.

[37] Safe Drinking Water Act, 42 U.S.C. 300f et seq.; 40 CFR §§144-148.

[38] Interstate Oil and Gas Compact Commission (2005). CO_2 Geological Sequestration Task Force, A Regulatory Framework for Carbon Capture and Storage.

[39] See the EPA publication Technical Program Overview: Underground Injection Control Regulations or their website available at http://www.epa.gov/safewater/uic.html for more details.

[40] See NRDC v. EPA, 907 F2d 1146 (DC Cir. 1990).

[41] Benson, S. M. et al., Lessons Learned from Natural and Industrial Analogues for Storage of Carbon Dioxide in Deep Geologic Formations at 103.

[42] Telephone and personal interviews with staff members of the West Virginia Division of Environmental Protection, and with staff of Consol Energy. N.B.: West Virginia does not have any Class I wells.

[43] See Hvorka, S. D. et al., Report to the Texas Commission on Environmental Quality to Accompany a Class V Application for an Experimental Technology Pilot Injection Well, December 2003.

[44] Wilson, E. J., Johnson, T., and Keith, D. W, Regulating the Ultimate Sink: Managing the Risks of Geologic CO_2 Storage, Environmental Science & Technology, 2003, 37, 3476-3483 at 3479. Monitoring may be ordered for specific classes of Class 1 hazardous wells, but this rarely happens. The minimum federal requirements for either Class 1 nonhazardous or Class 2 wells focus primarily on the mechanical integrity of the well.

[45] Wilson, E. the Department of Engineering and Public Policy at Carnegie Mellon University is currently researching these issues. She was kind enough to share an unpublished paper, Subsurface Property Rights: Implications for Geologic CO_2 Sequestration with the authors. Her paper informed much of the following discussion on property interests.

[46] Trespass is an interference with the plaintiff's right to possess a property interest.

[47] Nuisance is an interference with the plaintiff's right to use and enjoy a property interest.

[48] For a general discussion of terrestrial sequestration refer to the MRCSP resources available at http://198.87.0.58/Terrestrial.aspx.

[49] Entergy (2002). Press Release by Yolanda Pollard. (January 15). Available at http://www.entergy.com/ news_room/newsrelease.aspx?NR_ID=308.

[50] U. S. Department of Agriculture. Cqestr: a Model to Estimate Carbon Sequestration in Agricultural Soils. Available at http://www.ars.usda.gov/research/publications/publications. htm?SEQ_NO_115=112230.

[51] Oregon Administrative Rules, §345-024-0500 et seq.

[52] For a concise review of carbon capture and storage options see Herzog & Golomb (2004). Carbon Capture and Storage from Fossil Fuel Use. Massachusetts Institute of Technology Laboratory for Energy and the Environment. Available at http://sequestration.mit.edu/pdf/enclyclopedia_of_energy_article.pdf.

[53] IPCC. 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. Final Draft. October: Chapter 7.

The National Regulatory Research Institute
1080 Carmack Road
Columbus, Ohio 43210-1002
Phone: 614-292-9404
Fax: 614-292-7196
www.nrri.ohio-state.edu

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