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Direct Carbon Sequestration: Capturing and Storing CO_2

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Direct Carbon Sequestration: Capturing and Storing CO_2

Summary

Direct sequestration is capturing carbon at its source and storing it before its release to the atmosphere. Carbon capture and storage — also known as CCS — is attracting interest as a measure for mitigating global climate change, because potentially large amounts of CO_2 emitted from fossil fuel use in the United States could be eligible for sequestration. Electricity-generating plants may be the most likely initial candidates for direct sequestration because they are predominantly large, single-point sources, and they contribute approximately one-third of U.S. CO_2 emissions from fossil fuels.

Congressional interest is growing in direct sequestration as part of legislative strategies addressing climate change. Several bills introduced in the 109th Congress promoted carbon sequestration technologies for coal-fired power plants or coal gasification facilities. Other bills included provisions for establishing carbon sequestration programs, and one bill set goals for sequestering 60% of U.S. greenhouse gas emissions from stationary sources by 2020. Congress appropriated $67 million in FY2006 for the Department of Energy's (DOE's) carbon sequestration program.

Approaches for capturing CO_2 are available that can potentially remove 80%-95% of CO_2 emitted from a power plant or large industrial source. Pipelines or ships will likely transport captured CO_2 from capture to storage. Three main types of geological formations are likely candidates for storing large amounts of CO_2: oil and gas reservoirs, deep saline reservoirs, and unmineable coal seams. The deep ocean also has a huge potential to store carbon. Direct injection of CO_2 into the deep ocean, however, is in an experimental stage. Mineral carbonation — reacting minerals with a stream of concentrated CO_2 to form a solid carbonate — is a well understood process, but is in an experimental stage as a viable process for storing large quantities of CO_2.

DOE's carbon sequestration research program will be facilitating field tests for carbon sequestration, with seven regional partners, across the United States. The department is also undertaking a 10-year, $1 billion project — known as FutureGen — to build a coal-fired power plant that integrates carbon sequestration and hydrogen production while producing 275 megawatts of electricity, enough to power about 150,000 average U.S. homes. DOE estimates that direct sequestration costs between $100 and $300 per tonne of carbon emissions avoided using current technologies. (A tonne refers to a metric ton, or 1,000 kilograms, which is approximately 2,200 pounds.) Power plants with CCS would require more fuel, and costs per kilowatt-hour would likely rise compared to plants without CCS.

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Direct sequestration is capturing carbon at its source and storing it before its release to the atmosphere. Carbon capture and storage — also known as CCS — would reduce the amount of CO_2 emitted to the atmosphere while allowing the use of fossil fuels at some electricity-generating plants and industrial facilities. An integrated CCS system would include three main steps: (1) capturing and separating CO_2 at the plant; (2) transporting the captured CO_2 to the storage site; and (3) storing CO_2 in geological reservoirs or in the oceans. As a measure for mitigating global climate change, direct sequestration is attracting interest because several projects in the United States and abroad — typically associated with oil and gas production — are successfully injecting and storing CO_2 underground, albeit at relatively small scales. Also, potentially large amounts of CO_2 generated from fossil fuels — as much as one-third of the total CO_2 emitted in the United States — could be eligible for large-scale direct sequestration.[1]

Fossil fuel use accounts for 94% of all U.S. CO_2 emissions.[2] Electricity generation contributes the largest proportion of CO_2 emissions compared to other types of fossil fuel use in the United States (see **Table 1**.) Electricity-generating plants, thus, may be the most likely initial candidates for capture, separation, and storage, or reuse of CO_2 because they are predominantly large, single-point sources for emissions. Large industrial facilities, such as hydrogen production plants, that already produce concentrated CO_2 streams as part of the industrial process are also good candidates for CO_2 capture and storage.[3]

Congressional interest in direct sequestration, as part of legislation addressing climate change, is growing. Several bills introduced in the 109th Congress would have provided tax or financial incentives, or otherwise promoted carbon sequestration technologies for coal-fired power plants or coal gasification facilities. Other bills included provisions for establishing carbon sequestration programs and one bill would have set goals for sequestering 60% of U.S. greenhouse gas emissions from stationary sources by 2020. The Energy Policy Act of 2005 (P.L. 109-58) directed DOE to undertake a 10-year research and development program to enhance technological development of systems that capture or produce concentrated streams of CO_2 which can be stored. In FY2006, Congress appropriated $67 million for DOE's carbon sequestration program.

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[1] DOE estimates that large, fossil-fuel power plants account for one-third of all U.S. CO_2 emissions; see [http://www.fossil.energy.gov/programs/sequestration/overview.html].

[2] U.S. Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2004*; see [http://epa.gov/climatechange/emissions/usinventoryreport.html].

[3] Intergovernmental Panel on Climate Change (IPCC) Special Report: *Carbon Dioxide Capture and Storage*, 2005. (Hereafter referred to as "IPCC Special Report.")

This report covers only direct sequestration, and not indirect sequestration, whereby CO_2 is removed from the atmosphere and stored in vegetation, soils, or oceans. Forests (see CRS Report RL31432, *Carbon Sequestration in Forests*, by Ross Gorte) and agricultural lands store carbon, and the world's oceans exchange huge amounts of CO_2 from the atmosphere through natural processes.

Table 1. Sources for CO_2 Emissions in the United States from Combustion of Fossil Fuels

Sources	CO_2 Emissions[a]	Percent of Total
Electricity generation	2,290.6	41%
Transportation	1,855.5	33%
Industrial	863.5	15%
Residential	369.6	7%
Commercial	226.0	4%
Total	5,605.2	100%

Source: U.S. Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2004*, Table ES-3; see [http://epa.gov/climatechange/emissions/usinventoryreport.html].

a. CO_2 emissions in millions of metric tons ($MtCO_2$) for 2004; totals exclude emissions from U.S. territories.

Capturing and Separating CO_2

The first step in direct sequestration is to produce a concentrated stream of CO_2 for transport and storage. Currently, three main approaches are available to capture CO_2 from large-scale industrial facilities or power plants: (1) post-combustion capture, (2) pre-combustion capture, and (3) oxy-fuel combustion capture. For power plants, current commercial CO_2 capture systems could operate at 85%-95% capture efficiency.[4] Techniques for capturing CO_2 have not yet been applied to large power plants (e.g., 500 megawatts).[5]

Post-Combustion Capture. This process involves extracting CO_2 from the flue gas following combustion of fossil fuels or biomass. Several commercially available technologies, some involving absorption using chemical solvents, can in principle be used to capture large quantities of CO_2 from flue gases. U.S. commercial electricity-generating plants currently do not capture large volumes of CO_2 because they are not required to and there are no economic incentives to do so. Nevertheless, the post-combustion capture process includes proven technologies that are commercially available today, and costs can be reasonably estimated for scaling up for a large-scale application.

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[4] IPCC Special Report, p. 107.

[5] Ibid., p. 25.

Pre-Combustion Capture. This process separates CO_2 from the fuel by combining it with air and/or steam to produce hydrogen for combustion and CO_2 storage. The most common technologies today use steam reforming, in which steam is employed to extract hydrogen from natural gas.[6] In the absence of a requirement or economic incentives, pre-combustion technologies have not been used for power systems, such as natural gas combined-cycle power plants.

Oxy-Fuel Combustion Capture. This process uses oxygen instead of air for combustion and produces a flue gas that is mostly CO_2 and water, which are easily separable, after which the CO_2 can be compressed, transported, and stored. This technique is still considered developmental, in part because temperatures of pure oxygen combustion (about 3,500^o Celsius) are far too high for typical power plant materials.

Application of these technologies to power plants generating several hundred megawatts of electricity has not yet been demonstrated. Also, up to 80% of the total costs may be associated with the capture phase of the CCS process.[7] Costs are discussed below in more detail.

Transportation

Pipelines are the most common method for transporting CO_2 in the United States. Over 2,500 kilometers (about 1,500 miles) of pipeline transports more than 40 $MtCO_2$ each year,[8] predominantly to Texas, where CO_2 is used in enhanced oil recovery (EOR).[9] Transporting CO_2 in pipelines is similar to transporting petroleum products like natural gas and oil; it requires attention to design, monitoring for leaks, and protection against overpressure, especially in populated areas.[10]

Using ships may be feasible when CO_2 needs to be transported over large distances or overseas. Ships transport CO_2 today, but at a small scale because of limited demand. Liquified natural gas, propane, and butane are routinely shipped by marine tankers on a large scale worldwide. Rail cars and trucks can also transport CO_2, but this mode would probably be uneconomical for large-scale CCS operations.

Costs for pipeline transport vary, depending on construction, operation and maintenance, and other factors, including right-of-way costs, regulatory fees, and more. The quantity and distance transported will mostly determine costs, which will also depend on whether the pipeline is onshore or offshore, the level of congestion along the route, and whether mountains, large rivers, or frozen ground are

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[6] IPCC Special Report, p. 130.

[7] Steve Furnival, reservoir engineer at Senergy, Ltd., "Burying Climate Change for Good," *Physics World*; see [http://physicsweb.org/articles/world/19/9/3/1].

[8] One metric ton of CO_2 equivalent is written as 1 tCO_2; one million metric tons is written as 1 $MtCO_2$; one billion metric tons is written as 1 $GtCO_2$.

[9] IPCC Special Report, p. 29.

[10] Ibid., p. 181.

encountered. Shipping costs are unknown in any detail, however, because no large-scale CO_2 transport system (in $MtCO_2$ per year, for example) is operating. Ship costs might be lower than pipeline transport for distances greater than 1,000 kilometers and for less than a few $MtCO_2$ transported per year.[11]

Sequestration in Geological Formations

Three main types of geological formations are being considered for carbon sequestration: (1) oil and gas reservoirs, (2) deep saline reservoirs, and (3) unmineable coal seams. In each case, CO_2 would be injected, in a dense form, below ground into a porous rock formation that holds or previously held fluids. By injecting CO_2 below 800 meters in a typical reservoir, the pressure induces CO_2 to become supercritical — a relatively dense liquid — and thus less likely to migrate out of the geological formation. Injecting CO_2 into deep geological formations uses existing technologies that have been primarily developed by and used for the oil and gas industry, and that could potentially be adapted for long-term storage and monitoring of CO_2. Other underground injection applications in practice today, such as natural gas storage, deep injection of liquid wastes, and subsurface disposal of oil-field brines, can also provide information for sequestering CO_2 in geological formations.[12]

The storage capacity for CO_2 storage in geological formations is potentially huge if all the sedimentary basins in the world are considered.[13] The suitability of any particular site, however, depends on many factors including proximity to CO_2 sources and other reservoir-specific qualities like porosity, permeability, and potential for leakage. **Figure 1** is a snapshot of current or planned projects (most are associated with natural gas production) as of 2005 that involve CO_2 storage in geological formations. **Table 2** lists their characteristics. The subsections below briefly describe general characteristics of each of the three types of geological formations.

Oil and Gas Reservoirs.

Pumping CO_2 into oil and gas reservoirs to boost production (enhanced oil recovery, or EOR) is practiced in the petroleum industry today. The United States is a world leader in this technology and uses approximately 32 $MtCO_2$ annually for EOR, according to DOE.[14] The advantage of using this technique for long-term CO_2 storage is that sequestration costs can be partially offset by revenues from oil and gas production. CO_2 can also be injected into oil and gas reservoirs that are completely depleted, which would serve the purpose of long-term sequestration, but without any offsetting benefit from oil and gas production. CO_2 can be stored onshore or offshore; to date, most CO_2 projects associated with EOR are onshore, with the bulk of U.S. activities in west Texas (see **Figure 1**.)

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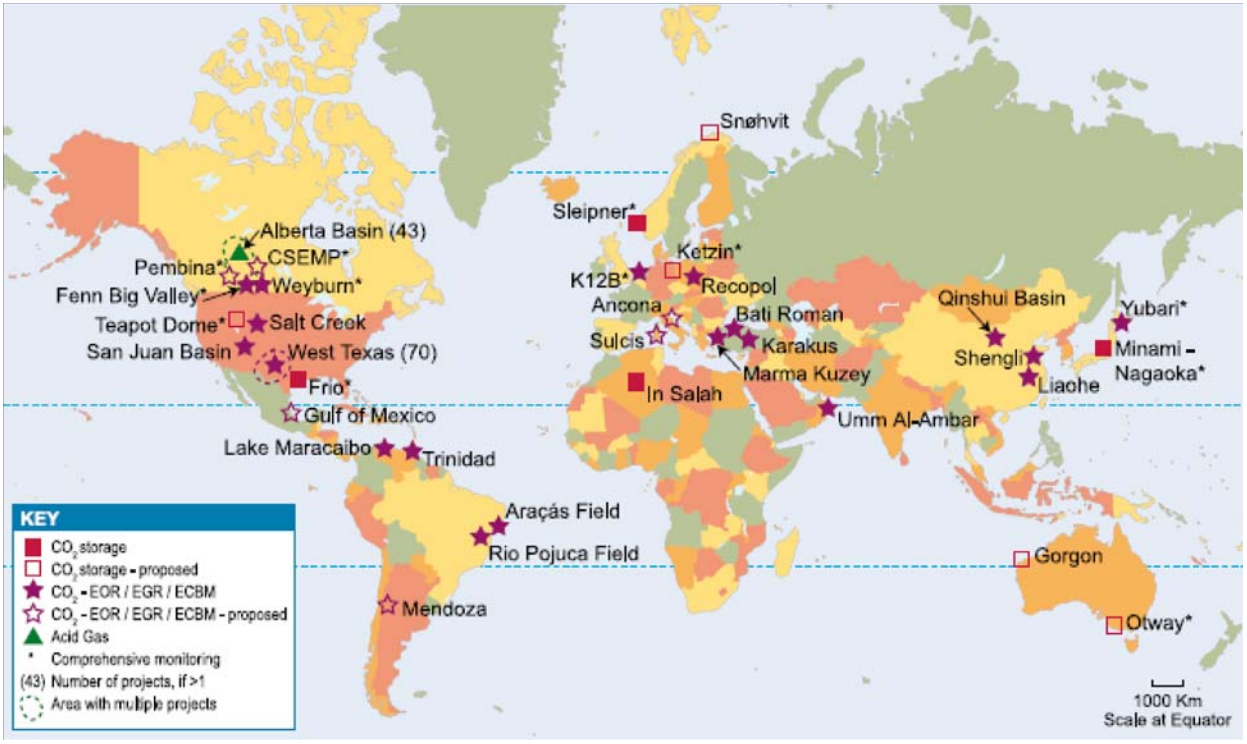
[11] IPCC Special Report, p. 31.

[12] Ibid.

[13] Sedimentary basins refer to natural large-scale depressions in the Earth's surface that are filled with sediments and fluids and are therefore potential reservoirs for CO_2 storage.

[14] See [http://www.fossil.energy.gov/programs/sequestration/geologic/index.html].

Figure 1. Sites Where Activities Involving CO_2 Storage Are Planned or Underway



Source: IPCC Special Report, Figure 5.1, p. 198.
Note: EOR is enhanced oil recovery; EGR is enhanced gas recovery; ECBM is enhanced coal bed methane recovery.

Depleted or abandoned oil and gas fields, especially in the United States, are prime candidates for CO_2 storage for several reasons:

- oil and gas originally trapped did not escape for millions of years, demonstrating the structural integrity of the reservoir;
- extensive studies have typically characterized the geology of the reservoir;
- computer models have often been developed to understand how hydrocarbons move in the reservoir, and the models could be applied to predicting how CO_2 could move; and
- infrastructure and wells from oil and gas extraction may be in place and might be used for handling CO_2 storage.

Some of these features could also be disadvantages to CO_2 sequestration. Wells that penetrate from the surface to the reservoir could be conduits for CO_2 release if they are not plugged properly. Care must be taken not to overpressure the reservoir during CO_2 injection, which could fracture the caprock — the part of the formation that formed a seal to trap oil and gas — and subsequently allow CO_2 to escape. Also, shallow oil and gas fields (those less than 800 meters deep, for example) may be unsuitable because CO_2 may form a gas instead of a denser liquid and could escape to the surface more easily.

Table 2. Current and Planned CO_2 Storage Projects

Project	Country	Scale of Project	Lead organizations	Injection start date	Approximate average daily injection rate	Total storage	Storage type	Geological storage formation	Age of formation	Lithology	Monitoring
Sleipner	Norway	Commercial	Statoil, IEA	1996	3000 t per day	20 Mt planned	Aquifer	Utsira Formation	Tertiary	Sandstone	4D seismic plus gravity
Weyburn	Canada	Commercial	EnCana, IEA	May 2000	3-5000 t per day	20 Mt planned	CO_2-EOR	Midale Formation	Mississippian	Carbonate	Comprehensive
Minami-Nagoaka	Japan	Demo	Research Institute of Innovative Technology for the Earth	2002	Max 40 t per day	10,000 t planned	Aquifer (Sth. Nagoaka Gas Field)	Haizume Formation	Pleistocene	Sandstone	Crosswell seismic + well monitoring
Yubari	Japan	Demo	Japanese Ministry of Economy, Trade and Industry	2004	10 t per day	200 t Planned	CO_2-ECBM	Yubari Formation (Ishikari Coal Basin)	Tertiary	Coal	Comprehensive
In Salah	Algeria	Commercial	Sonatrach, BP, Statoil	2004	3-4000 t per day	17 Mt planned	Depleted hydrocarbon reservoirs	Krechba Formation	Carboniferous	Sandstone	Planned comprehensive
Frio	USA	Pilot	Bureau of Economic Geology of the University of Texas	Oct. 4-13, 2004	Approx. 177 t per day for 9 days	1600t	Saline formation	Frio Formation	Tertiary	Brine-bearing sandstone-shale	Comprehensive
K12B	Netherlands	Demo	Gaz de France	2004	100-1000 t per day (2006+)	Approx 8 Mt	EGR	Rotleigendes	Permian	Sandstone	Comprehensive
Fenn Big Valley	Canada	Pilot	Alberta Research Council	1998	50 t per day	200 t	CO_2-ECBM	Mannville Group	Cretaceous	Coal	P, T, flow
Recopol	Poland	Pilot	TNO-NITG (Netherlands)	2003	1 t per day	10 t	CO_2-ECBM	Silesian Basin	Carboniferous	Coal	

Project	**Country**	**Scale of Project**	**Lead organizations**	**Injection start date**	**Approximate average daily injection rate**	**Total storage**	**Storage type**	**Geological storage formation**	**Age of formation**	**Lithology**	**Monitoring**
Qinshui Basin	China	Pilot	Alberta Research Council	2003	30 t per day	150 t	CO_2-ECBM	Shanxi Formation	Carboniferous-Permian	Coal	P, T, flow
Salt Creek	USA	Commercial	Anadarko	2004	5-6000 t per day	27 Mt	CO_2-EOR	Frontier	Cretaceous	Sandstone	Under development
Planned Projects (2005 onwards)											
Snøhvit	Norway	Decided Commercial	Statoil	2006	2000 t per day		Saline formation	Tubaen Formation	Lower Jurassic	Sandstone	Under development
Gorgon	Australia	Planned Commercial	Chevron	Planned 2009	Approx. 10,000 t per day		Saline formation	Dupuy Formation	Late Jurassic	Massive sandstone	Under development
Ketzin	Germany	Demo	GFZ Potsdam	2006	100 t per day	60 kt	Saline formation	Stuttgart Formation	Triassic	Sandstone	Comprehensive
Otway	Australia	Pilot	CO2CRC	Planned late 2005	160 t per day for 2 years	0.1 Mt	Saline fm and depleted gas field	Waarre Formation	Cretaceous	Sandstone	Comprehensive
Teapot Dome	USA	Proposed Demo	RMOTC	Proposed 2006	170 t per day for 3 months	10 kt	Saline fm and CO_2-EOR	Tensleep and Red Peak Fm	Permian	Sandstone	Comprehensive
CSEMP	Canada	Pilot	Suncor Energy	2005	50 t per day	10 kt	CO_2-ECBM	Ardley Fm	Tertiary	Coal	Comprehensive
Pembina	Canada	Pilot	Penn West	2005	50 t per day	50 kt	CO_2-EOR	Cardium Fm	Cretaceous	Sandstone	Comprehensive

Source: IPCC Special Report, Table 5.1, p. 201.
Note: EOR is enhanced oil recovery; EGR is enhanced gas recovery; ECBM is enhanced coal bed methane recovery.

The In Salah Project in Algeria is the world's first large-scale effort to store CO_2 in a gas reservoir.[15] (See **Table 2**.) At In Salah, CO_2 is separated from the produced natural gas and then reinjected into the same formation. Approximately 17 $MtCO_2$ are planned to be captured and stored over the lifetime of the project.

The Weyburn Project in south-central Canada uses CO_2 produced from a coal gasification plant in North Dakota for EOR, injecting up to 5,000 tCO_2 per day into the formation and recovering oil.[16] (See **Table 2**.) Approximately 20 $MtCO_2$ are expected to remain in the formation over the lifetime of the project.

Table 3 shows that the global potential for CO_2 storage in oil and gas fields may be 900 $GtCO_2$. Potential storage capacity in the United States could be approximately 11% of world potential, or about 100 $GtCO_2$.[17]

Table 3. Estimated Global Capacity for CO_2 Storage in Three Different Geological Formations

(annual CO_2 emissions for the U.S. and globally are shown for comparison)

Reservoir type	Lower estimate of storage capacity ($GtCO_2$)	Upper estimate of storage capacity ($GtCO_2$)	2004 CO_2 emitted from combustion of fossil fuels ($GtCO_2$)
Oil and gas fields	675	900	—
Deep saline formations	1,000	Uncertain, possibly 10,000	—
Unmineable coal seams	3	200	—
United States	—	—	5.6
Global (including U.S.)	—	—	27.0

Sources: IPCC Special Report, Table 5.2, p. 221; U.S. Energy Information Agency; see [http://www.eia.doe.gov/pub/international/iealf/tableh1co2.xls].

Deep Saline Reservoirs. Some rocks in sedimentary basins are saturated with brines or brackish water unsuitable for agriculture or drinking. As with oil and gas, deep saline reservoirs can be found onshore and offshore; in fact, they are often part of oil and gas reservoirs and share many characteristics. The oil industry routinely injects brines recovered during oil production into saline reservoirs for disposal.[18] Using saline reservoirs for CO_2 sequestration has several advantages:

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[15] IPCC Special Report, p. 203.

[16] IPCC Special Report, p. 204.

[17] Ibid., p. 222.

[18] DOE Office of Fossil Energy; see [http://www.fossil.energy.gov/programs/sequestration/geologic/index.html].

- They are more widespread in the United States than oil and gas reservoirs and thus have greater probability of being close to large point sources of CO_2.
- Saline reservoirs have potentially the largest reservoir capacity of the three types of geologic formations (at least 1,000 $GtCO_2$, and possibly ten times that globally; see **Table 3**).[19] DOE estimates that the U.S. storage capacity in saline reservoirs could be half of the minimum global estimate, or 500 $GtCO_2$, although some studies point to higher estimates, approaching 1,000 $GtCO_2$ in the United States.[20]

The Sleipner Project in the North Sea is the first commercial-scale operation for sequestering CO_2 in a deep saline reservoir (see **Table 2**.) As of 2005, Sleipner has stored more than 7 $MtCO_2$. Carbon dioxide is separated from natural gas production at the nearby Sleipner West Gas Field, then injected 800 meters below the seabed of the North Sea into a saline aquifer at 2,700 tCO_2 per day. Monitoring has indicated the CO_2 has not leaked from the saline reservoir, and computer simulations suggest that the CO_2 will eventually dissolve into the saline water, further reducing the potential for leakage.

Large CO_2 sequestration projects, similar to Sleipner, are being planned in western Australia (the Gorgon Project) and in the Barents Sea (the Snohvits Project), that will inject 10,000 and 2,000 tCO_2 per day, respectively, when at capacity. (See **Figure 1** and **Table 2**.) Both projects plan to strip CO_2 from produced natural gas and inject it into deep saline formations for permanent storage.

Although deep saline reservoirs have huge potential capacity to store CO_2 (**Table 3**), estimates of lower and upper capacities vary greatly, reflecting a high degree of uncertainty in how to measure storage capacity.[21] Actual storage capacity may have to be determined on a case-by-case basis.

In addition, some studies have pointed out potential problems with maintaining the integrity of the reservoir because of chemical reactions following CO_2 injection. Injecting CO_2 can acidify (lower the pH of) the fluids in the reservoir, dissolving minerals such as calcium carbonate, and possibly increasing permeability. Increased permeability could allow CO_2-rich fluids to escape the reservoir along new pathways and contaminate aquifers used for drinking water.

In an October 2004 experiment, researchers injected 1,600 tCO_2 1,500 meters deep into the Frio Formation — a saline reservoir containing oil and gas — along the Gulf Coast near Dayton, Texas, to test its performance for CO_2 sequestration and storage.[22] Test results indicated that calcium carbonate and other minerals rapidly

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[19] IPCC Special Report, p. 223.

[20] Ibid.

[21] Ibid.

[22] Y. K. Kharaka et al., "Gas-water interactions in the Frio Formation following CO_2

(continued...)

dissolved following injection of the CO_2. The researchers also measured increased concentrations of iron and manganese in the reservoir fluids, suggesting that the dissolved minerals had high concentrations of those metals. The results raised the possibility that toxic metals and other compounds might be liberated if CO_2 injection dissolved minerals that held high concentrations of those substances.

Another concern is whether the injected fluids, with pH lowered by CO_2, would dissolve cement used to seal the injection wells that pierce the formation from the ground surface. Leaky injection wells could then also become pathways for CO_2-rich fluids to migrate out of the saline formation and contaminate fresher groundwater above. Approximately six months after the injection experiment at the Dayton site, however, researchers did not detect any leakage upwards into the overlying formation, suggesting that the integrity of the saline reservoir formation remained intact at that time. Researchers are conducting further injection tests and monitoring whether the fluids are leaking.

Unmineable Coal Seams. **Table 3** shows that up to 200 $GtCO_2$ could be stored in unmineable coal seams around the globe. According to DOE, nearly 90% of U.S. coal resources are not mineable with current technology, because the coal beds are not thick enough, the beds are too deep, or the structural integrity of the coal bed[23] is inadequate for mining. Even if they cannot be mined, coal beds are commonly permeable and can trap gases, such as methane, which can be extracted (a resource known as coal bed methane, or CBM). Methane and other gases are physically bound (adsorbed) to the coal. Studies indicate that CO_2 binds even more tightly to coal than methane.[24] Carbon dioxide injected into permeable coal seams could displace methane, which could be recovered by wells and brought to the surface, providing a source of revenue to offset the costs of CO_2 injection.

An estimated 60-90 $GtCO_2$ could be stored, potentially, in North American coal seams.[25] Not all types of coal beds are suitable for CBM extraction, however. Without the coal bed methane resource, the sequestration process would be less economically attractive. Given economic considerations, total CO_2 storage capacity in North America may be only 3-15 $GtCO_2$.

Unmineable coal seam injection projects will need to assess several factors in addition to the potential for CBM extraction. These include depth, permeability, coal bed geometry (a few thick seams, not several thin seams), lateral continuity and vertical isolation (less potential for upward leakage), and other considerations. Once CO_2 is injected into a coal seam, it will likely remain there unless the seam is depressurized or the coal is mined. Also, many unmineable coal seams in the United States are located near electricity-generating facilities, which could reduce the distance and cost of transporting CO_2 from large point sources to storage sites.

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[22] (...continued)
injection: implications for the storage of greenhouse gases in sedimentary basins," *Geology*, v. 34, no. 7 (July, 2006), pp. 577-580.

[23] *Coal bed* and *coal seam* are interchangeable terms.

[24] IPCC Special Report, p. 217.

[25] Ibid., p. 224.

Carbon dioxide injection into coal beds has been successful in the Alberta Basin, Canada, and in a pilot project in the San Juan Basin of northern New Mexico. (See **Figure 1**.) However, no commercial CO_2 injection and sequestration project in coal beds is currently underway. Without ongoing commercial experience, storing CO_2 in coal seams has significant uncertainties compared to the other two types of geological storage discussed. Also, of the three methods, unmineable coal seams have the smallest potential capacity for storing CO_2.

Deep Ocean Sequestration

The world's oceans contain approximately 50 times the amount of carbon stored in the atmosphere and nearly 20 times the amount stored in plants and soils.[26] The oceans took up an average of 7 $GtCO_2$ per year from 1980 to 2000, and have stored approximately one-third, or more than 500 $GtCO_2$, of the total CO_2 released by humans to the atmosphere over the past 200 years.[27] Over time, experts predict that most CO_2 released to the atmosphere from fossil fuel combustion will eventually be absorbed in the ocean. But the rate of uptake depends on how fast the ocean mixes the surface waters with the deep ocean, a process that takes decades to centuries.

Injecting CO_2 directly into the deep ocean is considered a potentially viable process for long-term sequestration of large amounts of captured CO_2. The potential for ocean storage of captured CO_2 is huge, on the order of thousands of $GtCO_2$, but environmental impacts on marine ecosystems and other issues may determine whether large quantities of captured CO_2 will ultimately be stored in the oceans.

Direct Injection. Injecting CO_2 directly into the ocean would take advantage of the slow rate of mixing, allowing the injected CO_2 to remain sequestered until the surface and deep waters mix and CO_2 concentrations equilibrate with the atmosphere. What happens to the CO_2 would depend on how it is released into the ocean, the depth of injection, and the temperature of the seawater. The fraction of CO_2 stored and retained in the ocean tends to be higher with deeper injection. **Table 4** shows estimates of the fraction of CO_2 retained in the ocean (0.99 is 99% retained), over time, for different injection depths according to one set of ocean models.

Table 4. Fraction of CO_2 Retained for Ocean Storage

	Injection depth		
Year	**800 m**	**1500 m**	**3000 m**
2100	0.78 ± 0.06	0.91 ± 0.05	0.99 ± 0.01
2200	0.50 ± 0.06	0.74 ± 0.07	0.94 ± 0.06
2300	0.36 ± 0.06	0.60 ± 0.08	0.87 ± 0.10
2400	0.28 ± 0.07	0.49 ± 0.09	0.79 ± 0.12
2500	0.23 ± 0.07	0.42 ± 0.09	0.71 ± 0.14

Source: IPCC Special Report, Table TS.7, p. 38.
Note: Models assume 100 years of continuous injection at three different depths beginning in 2000.

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[26] Ibid., p. 281.

[27] IPCC Special Report, p. 37.

Carbon dioxide injected above 500 meters in depth typically would be released as a gas, and would rise towards the surface. Most of it would dissolve into seawater if the injected CO_2 gas bubbles were small enough.[28] Below 500 meters in depth, CO_2 can exist as a liquid in the ocean, although it is less dense than seawater. After injection at 500 meters, CO_2 would also rise, but an estimated 90% would dissolve in the first 200 meters. Below 3,000 meters in depth, CO_2 is both a liquid and is denser than seawater; the injected CO_2 would sink and dissolve in the water column or possibly form a CO_2 pool or lake on the sea bottom. Some researchers have proposed injecting CO_2 into the ocean bottom sediments below depths of 3,000 meters, and immobilizing the CO_2 as a dense liquid or solid CO_2 hydrate.[29] Deep storage in ocean bottom sediments, below 3,000 meters in depth, might potentially sequester CO_2 for thousands of years.[30]

Limitations to Deep Ocean Sequestration. In addition to uncertainties about cost, other concerns about storing CO_2 in the oceans include the length of time that injected CO_2 remains in the ocean, the quantity retained, and environmental impacts from elevated CO_2 concentrations in the seawater. Also, deep ocean storage is in a research stage. The types of problems associated with scaling up from small research experiments, using less than 100 liters of CO_2,[31] to injecting several $GtCO_2$ into the deep ocean are unknown.

Injecting CO_2 into the deep ocean would change ocean chemistry, locally at first, and assuming hundreds of $GtCO_2$ were injected, would eventually produce measurable changes over the entire ocean. The most significant and immediate effect would be the lowering of pH, increasing the acidity of the water. A lower pH may harm some ocean organisms, depending on the magnitude of the pH change and the type of organism. Actual impacts of deep sea CO_2 sequestration are largely unknown, however, because scientists know very little about deep ocean ecosystems.[32]

Environmental concerns led to the cancellation of the largest planned experiment to test the feasibility of ocean sequestration in 2002. A scientific consortium had planned to inject 60 tCO_2 into water over 800 meters deep near the Kona coast on the island of Hawaii. Environmental organizations opposed the experiment on the grounds that it would acidify Hawaii's fishing grounds, and that it would divert attention from reducing greenhouse gas emissions.[33] A similar but

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[28] Ibid., p. 285.

[29] A *CO_2 hydrate* is a crystalline compound formed at high pressures and low temperatures by trapping CO_2 molecules in a cage of water molecules.

[30] K. Z. House, et al., "Permanent carbon dioxide storage in deep-sea sediments," *Proceedings of the National Academy of Sciences*, vol. 103, no. 33 (Aug. 15, 2006): p. 12291-12295.

[31] P. G. Brewer, et al., "Deep ocean experiments with fossil fuel carbon dioxide: creation and sensing of a controlled plume at 4 km depth," *Journal of Marine Research*, vol. 63, no. 1 (2005): p. 9-33.

[32] IPCC Special Report, p. 298.

[33] Virginia Gewin, "Ocean carbon study to quit Hawaii," *Nature*, vol. 417 (June 27, 2002):

(continued...)

smaller project with plans to release more than 5 tCO_2 into the deep ocean off the coast of Norway, also in 2002, was cancelled by the Norway Ministry of the Environment after opposition from environmental groups.[34]

Mineral Carbonation

Another option for sequestering CO_2 produced by fossil fuel combustion involves converting CO_2 to solid inorganic carbonates, such as $CaCO_3$ (limestone), using chemical reactions. This process, known as "weathering," also occurs naturally but could take place over thousands or millions of years. The process can be accelerated by reacting a high concentration of CO_2 with minerals found in large quantities on the Earth's surface, such as olivine or serpentine.[35] Mineral carbonation has the advantage of sequestering carbon in solid, stable minerals that can be stored without risk of releasing carbon to the atmosphere over geologic time scales.

Mineral carbonation involves three major activities: (1) preparing the reactant minerals — mining, crushing, and milling — and transporting them to a processing plant, (2) reacting the concentrated CO_2 stream with the prepared minerals, and (3) separating the carbonate products and storing them in a suitable repository.

Mineral carbonation is well understood and can be applied at small scales, but is at an early phase of development as a technique for sequestering large amounts of captured CO_2. Large volumes of silicate oxide minerals are needed, from 1.6 to 3.7 tonnes (metric tons) of silicates per tCO_2 sequestered. Thus, a large-scale mineral carbonation process needs a large mining operation to provide the reactant minerals in sufficient quantity.[36] Large volumes of solid material would also be produced, between 2.6 and 4.7 tonnes of materials per tCO_2 sequestered, or 50%-100% more material to be disposed of by volume than originally mined. Because mineral carbonation is in the research and experimental stage, reasonably estimating the amount of CO_2 that could be sequestered by this technique is difficult.

Costs for Direct Sequestration

DOE estimates that sequestration costs — for capture, transport, and storage — range from \$100 to \$300 per tonne of carbon emissions avoided using present technology.[37] In most carbon sequestration systems, the cost of capturing CO_2 is the

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[33] (...continued)
p. 888.

[34] Jim Giles, "Norway sinks ocean carbon study," *Nature*, vol. 419 (Sep. 5, 2002): p. 6.

[35] Serpentine and olivine are silicate oxide minerals — combinations of the silica, oxygen, and magnesium — that react with CO_2 to form magnesium carbonates. Wollastonite, a silica oxide mineral containing calcium, reacts with CO_2 to form calcium carbonate (limestone). Magnesium and calcium carbonates are stable minerals over long time scales.

[36] IPCC Special Report, p. 40.

[37] Equivalent to \$27 to \$82 per tCO_2 emissions avoided.

largest component, possibly accounting for as much as 80% of the total.[38] Cost information is sparse for large, integrated, commercial CCS systems because few are currently operating, but estimates are available for the components of hypothetical systems. **Table 5** shows a range of estimated costs of each component of a CCS system, using data from 2002, and assuming that prices for geological storage are not offset by revenues from enhanced oil recovery or coal bed methane extraction.

Table 5. Estimated Cost Ranges for Components of a Carbon Capture and Storage System
(data from 2002)

CCS system components	Cost range	Remarks
Capture from a coal- or gas-fired power plant	15-75 US\$/tCO_2 net captured	Net costs of captured CO_2, compared to the same plant without capture.
Capture from hydrogen and ammonia production or gas processing	5-55 US\$/tCO_2 net captured	Applies to high-purity sources requiring simple drying and compression.
Capture from other industrial sources	25-115 US\$/tCO_2 net captured	Range reflects use of a number of different technologies and fuels.
Transportation	1-8 US\$/tCO_2 transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) MtCO_2 yr^{-1}.
Geological storage[a]	0.5-8 US\$/tCO_2 net injected	Excluding potential revenues from EOR or ECBM.
Geological storage: monitoring and verification	0.1-0.3 US\$/tCO_2 injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements.
Ocean storage	5-30 US\$/tCO_2 net injected	Including offshore transportation of 100-500 km, excluding monitoring and verification.
Mineral carbonation	50-100 US\$/tCO_2 net mineralized	Range for the best case studied. Includes additional energy use for carbonation.

Source: IPCC Special Report, Table TS.9, p. 42.
Note: Costs are as applied to a type of power plant or industrial source, and represent costs for large-scale, new installations, with assumed gas prices of \$3-4.75 per MCF (thousand cubic feet), and assumed coal prices of \$21.80-32.70 per short ton (2,000 pounds).

The wide range of costs for each component reflects the wide variability of site-specific factors. With the exception of certain industrial applications, such as capturing CO_2 from natural gas production facilities (see Sleipner example, above), CCS has not been used at a large scale. No large electricity-generating plants, the likely candidates for large-scale carbon sequestration, have incorporated CCS. Retrofitting existing plants with CO_2 capture systems would probably lead to higher costs than newly built power plants that incorporate CCS systems, and industrial sources of CO_2 may be more easily retrofitted. Cost disadvantages of retrofitting may be reduced for relative new and highly efficient existing plants.[39]

Capturing CO_2 at electricity-generating power plants will likely require more energy, per unit of power output, than required by plants without CCS. The

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[38] Furnival, "Burying Climate Change for Good."

[39] IPCC Special Report, p. 10.

additional energy required also means that more CO_2 would be produced, per unit of power output. As a result, plants with CCS would be less efficient than plants without CCS. Comparisons of costs between power plants with and without CCS often include "avoided CO_2 emissions" as well as captured CO_2 emissions. Avoided CO_2 emissions takes into account the additional fuel needed to generate the additional energy required to capture CO_2. Appendix A provides more information about avoided versus captured CO_2 emissions.

Table 6 compares CO_2 avoided versus CO_2 captured for three different types of power plants, and the increased fuel required for capturing CO_2 at the plant. **Table 7** compares the cost of electricity for plants without CCS — capture, transport, and storage — against plants with CCS.

Table 6. Comparison of CO_2 Captured Versus CO_2 Avoided for New Power Plants

Power plants	Pulverized coal	Natural gas combined cycle	Integrated coal gasification combined cycle
CO_2 captured	0.82-0.97 kg/kWh	0.36-0.41 kg/kWh	0.67-0.94 kg/kWh
CO_2 avoided	0.62-0.70 kg/kWh	0.30-0.32 kg/kWh	0.59-0.73 kg/kWh
Increased fuel requirement for capture	24-40%	11-22%	14-25%

Source: From IPCC Special Report, Table 8.3a, p. 347.
Note: kWh is kilowatt hour; kg is kilogram.

Table 7. Comparison of Electricity Costs for New Power Plants With and Without Carbon Capture and Geological Storage

Power plants	Pulverized coal	Natural gas combined cycle	Integrated coal gasification combined cycle
Cost of electricity (plant without CCS)	0.043-0.052 \$/kWh	0.031-0.050 \$/kWh	0.041-0.061 \$/kWh
Cost of electricity (plant with CCS)	0.063-0.099 \$/kWh	0.043-0.077 \$/kWh	0.055-0.091 \$/kWh

Source: From IPCC Special Report, Table 8.3a, p. 347.

DOE states that the goal of its carbon sequestration program is to reduce costs to \$10 or less per tonne of carbon emissions avoided by 2015.[40] That goal is 10% of DOE's lower estimate of today's carbon sequestration costs. Other sources suggest that costs of building and operating CO_2 capture systems will decline over time with sustained research and development, and with technological improvements.[41]

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[40] Equivalent to \$2.70 per tCO_2 avoided; see [http://www.fossil.energy.gov/programs/sequestration/overview.html].

[41] IPCC Special Report, p. 41.

Costs of capturing CO_2 at a large electricity-generating plant would probably dominate the overall cost of comprehensive CCS system. Thus, improving the efficiency of the CO_2 capture phase may produce the largest cost savings. However, the variability of site-specific factors, such as types and costs of fuels used by power plants, distance of transport to a storage site, and the type of CO_2 storage, also suggests that costs will vary widely from project to project.

Research Programs and Demonstration Projects

Figure 1 and **Table 2** list a number of geologic sequestration projects that are planned or underway around the globe. Many are commercial projects that include aspects of enhanced oil recovery and some are related to coal bed methane extraction. The U.S. petroleum industry, for example, injects 32 $MtCO_2$ per year of CO_2 underground for EOR, particularly in west Texas.[42] The Sleipner Project in Norway, using CO_2 stripped from natural gas production, sequesters approximately 3,000 tCO_2 per day of in a deep saline aquifer. Norway's carbon tax of nearly 40 euro per tCO_2[43] was a strong economic incentive for the project; sequestration avoids nearly $50 million per year in carbon taxes.[44] The Gorgon Project in western Australia, also planning to use a deep saline aquifer, would inject 10,000 tCO_2 per day recovered from natural gas operations. Gorgon, expected to begin operations between 2008 and 2010, would be the world's largest CO_2 sequestration project.

DOE Carbon Sequestration Program. DOE's carbon sequestration program has grown to over $60 million per year since 1997, when it was less than $5 million. The program has three main elements: (1) laboratory and pilot-scale research for developing new technologies and systems; (2) infrastructure development for future deployment of carbon sequestration using regional partnerships; and (3) support for the DOE FutureGen project, a 10-year initiative to build the world's first integrated carbon sequestration and hydrogen production power plant (discussed below). The program seeks results from its program by 2012 that will lead to three goals: (1) ensure 90% capture of CO_2 from power plants; (2) store 99% of the sequestered CO_2 over 100 years; and (3) add no more than 10% to costs.[45]

The research aspect of the DOE program includes a combination of cost-shared projects, industry-led development projects, research grants, and research at the National Engineering Technology Laboratory. The program investigates CO_2 capture, storage, monitoring, mitigation, and verification, and includes work on non-CO_2 greenhouse gases and on advancing breakthrough technologies.

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[42] See [http://www.fossil.energy.gov/programs/sequestration/geologic/index.html].

[43] See CRS Report RL33581, *Climate Change: The European Union's Emissions Trading System (EU-ETS), Appendix: Norway's Trading System*, by Larry Parker.

[44] Furnival, "Burying Climate Change for Good."

[45] DOE Carbon Sequestration Technology Roadmap and Program Plan 2006, p. 9; see [http://www.fossil.energy.gov/programs/sequestration/publications/programplans/2006/2006_sequestration_roadmap.pdf].

Beginning in 2003, DOE created seven regional partnerships to identify opportunities for carbon sequestration field tests in the United States and Canada.[46] According to DOE, the first phase of the partnership program identified the potential for sequestering 600 $GtCO_2$ across the United States. On October 31, 2006, DOE announced it will provide $450 million over the next 10 years for field tests in the seven regions to validate results from smaller tests in the first phase. **Figure 2** shows the validation phase field tests by region.

Following the field test phase and starting in 2009, DOE plans to conduct large-volume sequestration tests (up to 1 $MtCO_2$) to demonstrate that the identified sites can store large quantities of CO_2.

FutureGen. On February 27, 2003, President Bush proposed a 10-year, $1 billion project to build a coal-fired power plant that integrates carbon sequestration and hydrogen production while producing 275 megawatts of electricity, enough to power about 150,000 average U.S. homes. The plant will be a coal-gasification facility and will produce between 1 and 2 $MtCO_2$ annually. DOE will provide most of the funding. An industry consortium, the FutureGen Industrial Alliance, Inc.,[47] is expected to contribute up to $250 million, and international partners may contribute up to 8% of the project's cost.[48] Congress directed $9 million to initiate FutureGen in the conference report (H.Rept. 108-330) for the 2004 Interior Appropriations Act, and most recently appropriated $18 million for the project in FY2006. The FY2007 budget request included $54 million for FutureGen.

The FutureGen Industrial Alliance will conduct the first phase of the project. In July 2006, from a list of 12 sites in seven states, they announced four finalists who will compete to host the FutureGen plant.[49] DOE will conduct a National Environmental Policy Act (NEPA) environmental analysis, will specify further site characterization, and will provide public scoping meetings at the four sites in anticipation of producing an Environmental Impact Statement for the plant after final site selection. Following the NEPA review, the FutureGen Alliance will select the final site, possibly in the latter half of 2007.

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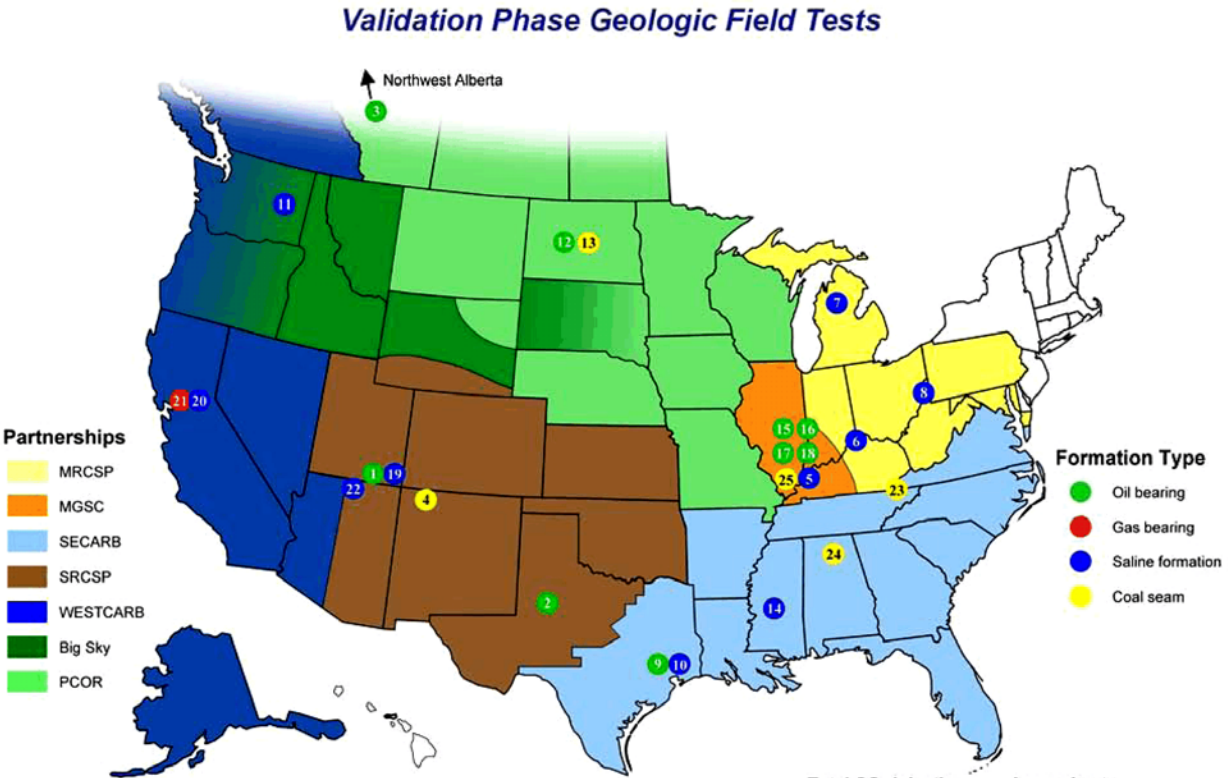
[46] The seven partnerships are Midwest Regional Carbon Sequestration Partnership; Midwest (Illinois Basin) Geologic Sequestration Consortium; Southeast Regional Carbon Sequestration Partnership; Southwest Regional Carbon Sequestration Partnership; West Coast Regional Carbon Sequestration Partnership; Big Sky Regional Carbon Sequestration Partnership; and Plains CO_2 Reduction Partnership; see [http://www.fossil.energy.gov/programs/sequestration/partnerships/index.html].

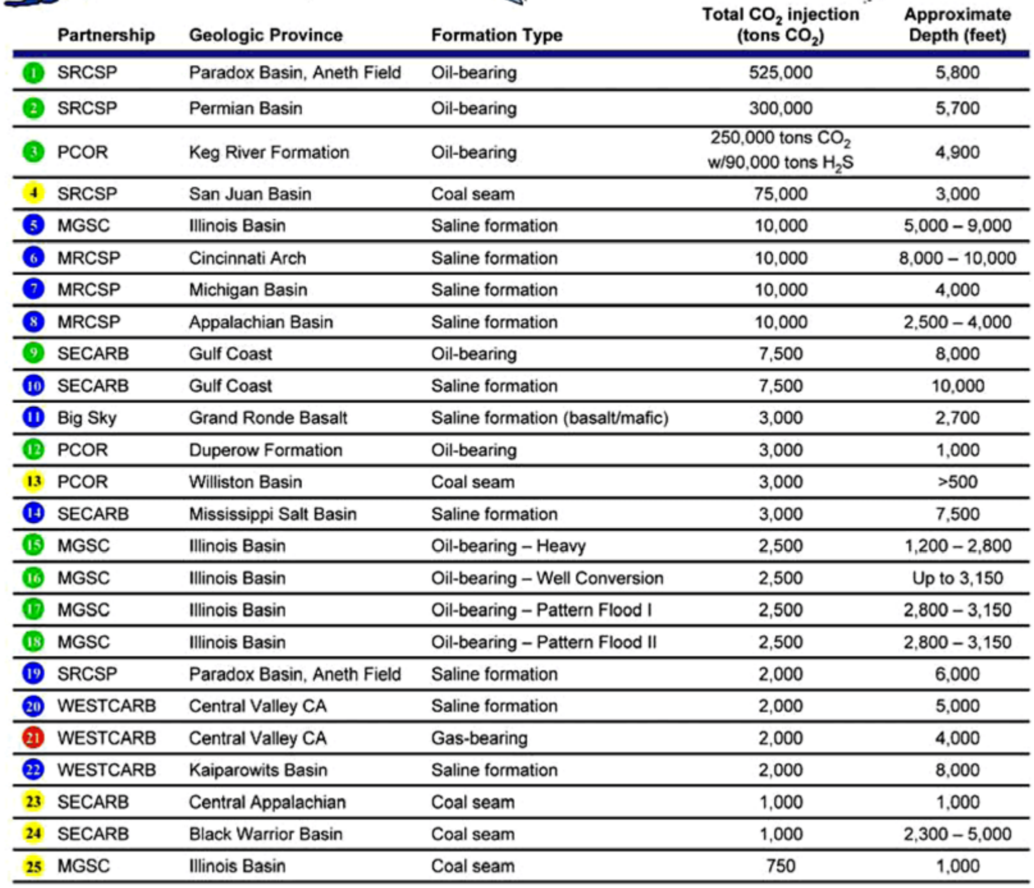
[47] As of Dec. 2006, 12 companies form the FutureGen Industrial Alliance: American Electric Power; Southern Company; CONSOL Energy, Inc.; Rio Into Energy America (RHEA); Peabody Energy; EON US; PAL Corporation; BHP Billiton; Foundation Coal Corp.; China Hennaing Group; Anglo American; and Xstrata Coal. See [http://www.futuregenalliance.org/].

[48] DOE report to Congress, March 2004. See [http://www.fossil.energy.gov/programs/powersystems/futuregen/futuregen_report_march_04.pdf].

[49] The four finalists are Mattoon, IL; Tuscola, IL; Heart of Brazos (near Jewett, TX); and Odessa, TX.

Figure 2. DOE Carbon Sequestration Program Field Tests





	Partnership	Geologic Province	Formation Type	Total CO_2 injection (tons CO_2)	Approximate Depth (feet)
1	SRCSP	Paradox Basin, Aneth Field	Oil-bearing	525,000	5,800
2	SRCSP	Permian Basin	Oil-bearing	300,000	5,700
3	PCOR	Keg River Formation	Oil-bearing	250,000 tons CO_2 w/90,000 tons H_2S	4,900
4	SRCSP	San Juan Basin	Coal seam	75,000	3,000
5	MGSC	Illinois Basin	Saline formation	10,000	5,000 – 9,000
6	MRCSP	Cincinnati Arch	Saline formation	10,000	8,000 – 10,000
7	MRCSP	Michigan Basin	Saline formation	10,000	4,000
8	MRCSP	Appalachian Basin	Saline formation	10,000	2,500 – 4,000
9	SECARB	Gulf Coast	Oil-bearing	7,500	8,000
10	SECARB	Gulf Coast	Saline formation	7,500	10,000
11	Big Sky	Grand Ronde Basalt	Saline formation (basalt/mafic)	3,000	2,700
12	PCOR	Duperow Formation	Oil-bearing	3,000	1,000
13	PCOR	Williston Basin	Coal seam	3,000	>500
14	SECARB	Mississippi Salt Basin	Saline formation	3,000	7,500
15	MGSC	Illinois Basin	Oil-bearing – Heavy	2,500	1,200 – 2,800
16	MGSC	Illinois Basin	Oil-bearing – Well Conversion	2,500	Up to 3,150
17	MGSC	Illinois Basin	Oil-bearing – Pattern Flood I	2,500	2,800 – 3,150
18	MGSC	Illinois Basin	Oil-bearing – Pattern Flood II	2,500	2,800 – 3,150
19	SRCSP	Paradox Basin, Aneth Field	Saline formation	2,000	6,000
20	WESTCARB	Central Valley CA	Saline formation	2,000	5,000
21	WESTCARB	Central Valley CA	Gas-bearing	2,000	4,000
22	WESTCARB	Kaiparowits Basin	Saline formation	2,000	8,000
23	SECARB	Central Appalachian	Coal seam	1,000	1,000
24	SECARB	Black Warrior Basin	Coal seam	1,000	2,300 – 5,000
25	MGSC	Illinois Basin	Coal seam	750	1,000

Source: DOE Carbon Sequestration Technology Roadmap and Program Plan 2006, Figure 14, p. 33.
Note: MRCSP is Midwest Regional Carbon Sequestration Partnership; MGSC is Midwest (Illinois Basin) Geologic Sequestration Consortium; SECARB is Southeast Regional Carbon Sequestration Partnership; SRCSP is Southwest Regional Carbon Sequestration Partnership; WESTCARB is West Coast Regional Carbon Sequestration Partnership; Big Sky is Big Sky Regional Carbon Sequestration Partnership; PCOR is Plains CO_2 Reduction Partnership.

Conclusion

In 2004, the United States emitted over 5.6 $GtCO_2$ from fossil fuel combustion, and electricity generation constituted nearly 40% of the total, or almost 2.3 $GtCO_2$. By far the largest sources of CO_2 amenable to direct carbon sequestration are fossil fuel power plants.[50] In addition to efforts that reduce CO_2 emissions by increasing the share of energy production from renewable sources, improving efficiency, and fostering conservation, U.S. strategies to mitigate climate change in the near future may include direct carbon sequestration. The federal government is already committing resources towards that goal through the 10-year, $1 billion FutureGen project, and with DOE's carbon sequestration program, funded at $67 million in FY2006. The only projects that directly inject large quantities of CO_2 into the subsurface in the United States today, however, are associated with enhancing oil and gas recovery.

An integrated direct sequestration system would include three main steps: (1) capturing and separating CO_2 at the plant; (2) transporting the captured CO_2 to the storage site; and (3) storing CO_2 in geological reservoirs or in the oceans. Technologies to separate and compress CO_2 are commercially available, but they have not been applied to large scale CO_2 capture from power plants for the purpose of long term storage.[51] Commercial operations that inject CO_2 to enhance oil recovery have the economic incentive of increasing revenues from oil production. Injecting CO_2 to enhance coal bed methane recovery has a similar incentive, although large scale commercial CO_2 injection projects to recover coal bed methane have not yet been implemented. In contrast, the current economic incentives for direct carbon sequestration to mitigate climate change are not clear. Norway's carbon tax has provided an incentive to sequester CO_2 from one of its natural gas operations: the Sleipner Project in Norway avoids nearly $50 million per year in carbon taxes by stripping CO_2 and storing it offshore in a deep saline aquifer.

Three main types of geological formations are being considered for carbon sequestration: (1) oil and gas reservoirs, (2) deep saline reservoirs, and (3) unmineable coal seams. Estimates of the total reservoir capacity vary widely and are subject to large uncertainties — possibly up to several orders of magnitude — reflecting an incomplete understanding of how to measure storage capacity. The world's oceans have the largest potential capacity to store CO_2, especially the deep ocean below 3,000 meters. However, deep ocean sequestration of large amounts of CO_2 is in a research stage, and environmental concerns about acidification and

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[50] H. J. Herzog and D. Golumb, "Carbon Capture and Storage from Fossil Fuel Use," in C.J. Cleveland (ed.), *Encyclopedia of Energy*, New York, NY: Elsevier Science, Inc. (2004), p. 277-287.

[51] Ibid.

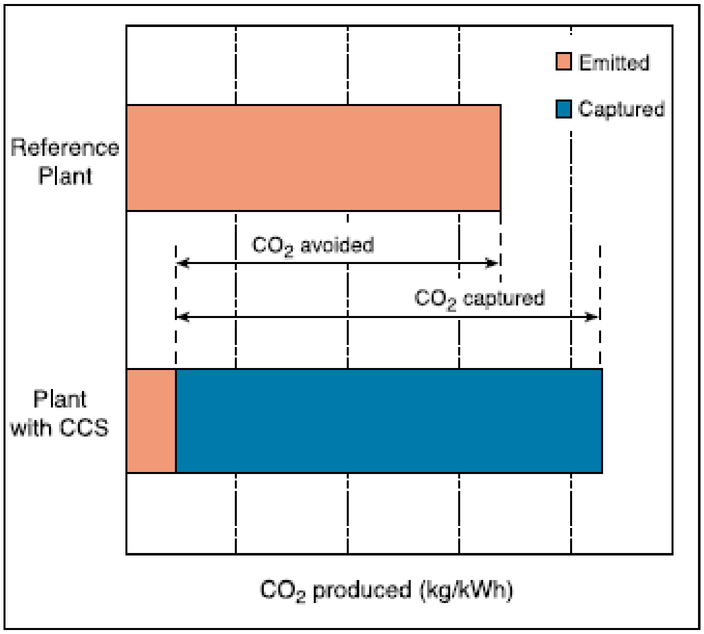
impacts to marine ecosystems stymied ocean sequestration experiments off the coast of Hawaii and Norway in 2002.

DOE plans to conduct direct carbon sequestration field tests over the next several years in seven regional partnerships across the country. DOE also plans to identify a final site for the FutureGen project, with the FutureGen Industrial Alliance, which would be the world's first large scale emission-free fossil fuel power plant.

Appendix A. Avoided CO_2

Figure 3 compares captured CO_2 and avoided CO_2 emissions. Additional energy required for capture, transport, and storage of CO_2 results in additional CO_2 production from a plant with CCS. The lower bar in **Figure 3** shows the larger amount of CO_2 produced per unit of power (kWh) relative to the reference plant (upper bar) without CCS. Unless no additional energy is required to capture, transport, and store CO_2, the amount of CO_2 avoided is always less than the amount of CO_2 captured. Thus the cost per tCO_2 avoided is always more than the cost per tCO_2 captured.[52]

Figure 3. Avoided Versus Captured CO_2



Source: IPCC Special Report, Figure 8.2.

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[52] IPCC Special Report, p. 346-347.