



Carbon Capture and Sequestration (CCS): A Primer

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Summary

Carbon capture and sequestration (or storage)—known as CCS—has attracted congressional interest as a measure for mitigating global climate change because large amounts of carbon dioxide (CO₂) emitted from fossil fuel use in the United States are potentially available to be captured and stored underground and prevented from reaching the atmosphere. Large, industrial sources of CO₂, such as electricity-generating plants, are likely initial candidates for CCS because they are predominantly stationary, single-point sources. Electricity generation contributes over 40% of U.S. CO₂ emissions from fossil fuels. Currently, U.S. power plants do not capture large volumes of CO₂ for CCS.

Several projects in the United States and abroad—typically associated with oil and gas production—are successfully capturing, injecting, and storing CO₂ underground, albeit at relatively small scales. The oil and gas industry in the United States injects nearly 50 million tons of CO₂ underground each year for the purpose of enhanced oil recovery (EOR). The volume of CO₂ envisioned for CCS as a climate mitigation option is overwhelming compared to the amount of CO₂ used for EOR. According to the U.S. Department of Energy (DOE), the United States has the potential to store billions of tons of CO₂ underground and keep the gas trapped there indefinitely. Capturing and storing the equivalent of decades or even centuries of CO₂ emissions from power plants (at current levels of emissions) suggests that CCS has the potential to reduce U.S. greenhouse gas emissions substantially while allowing the continued use of fossil fuels.

An integrated CCS system would include three main steps: (1) capturing and separating CO₂ from other gases; (2) purifying, compressing, and transporting the captured CO₂ to the sequestration site; and (3) injecting the CO₂ in subsurface geological reservoirs or storing it in the oceans. Deploying CCS technology on a commercial scale would be a vast undertaking. The CCS process, although simple in concept, would require significant investments of capital and of time. Capital investment would be required for the technology to capture CO₂ and for the pipeline network to transport the captured CO₂ to the disposal site. Time would be required to assess the potential CO₂ storage reservoir, inject the captured CO₂, and monitor the injected plume to ensure against leaks to the atmosphere or to underground sources of drinking water, potentially for years or decades until injection activities cease and the injected plume stabilizes.

Three main types of geological formations in the United States are being considered for storing large amounts of CO₂: oil and gas reservoirs, deep saline reservoirs, and unmineable coal seams. The deep ocean also has a huge potential to store carbon; however, direct injection of CO₂ into the deep ocean is controversial, and environmental concerns have forestalled planned experiments in the open ocean. Mineral carbonation—reacting minerals with a stream of concentrated CO₂ to form a solid carbonate—is well understood, but it is still an experimental process for storing large quantities of CO₂.

Large-scale CCS injection experiments are underway in the United States to test how different types of reservoirs perform during CO₂ injection of 1 million tons of CO₂ per year or more. Results from the experiments will undoubtedly be crucial to future permitting and site approval regulations. Acceptance by the general public of large-scale deployment of CCS may be a significant challenge. Some of the large-scale injection tests could garner information about public acceptance, as citizens become familiar with the concept, process, and results of CO₂ injection tests in their local communities.

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Introduction

Carbon capture and sequestration (or storage)—known as CCS—is a physical process that involves capturing manmade carbon dioxide (CO₂) at its source and storing it before its release to the atmosphere. CCS could reduce the amount of CO₂ emitted to the atmosphere despite the continued use of fossil fuels. An integrated CCS system would include three main steps: (1) capturing CO₂ and separating it from other gases; (2) purifying, compressing, and transporting the captured CO₂ to the sequestration site; and (3) injecting the CO₂ in subsurface geological reservoirs or storing it in the oceans. As a measure for mitigating global climate change, CCS has attracted congressional interest and support because several projects in the United States and abroad—typically associated with oil and gas production—are successfully capturing, injecting, and storing CO₂ underground, albeit at relatively small scales. The oil and gas industry in the United States injects nearly 50 million metric tons of CO₂ underground each year to help recover oil and gas resources (a process known as enhanced oil recovery, or EOR).¹ Potentially, much larger amounts of CO₂ produced from electricity generation—approximately 2.1 billion metric tons per year, about 40% of the total CO₂ emitted in the United States from fossil fuels (see **Table 1**)—could be targeted for large-scale CCS.

Fuel combustion accounts for 94% of all U.S. CO₂ emissions.² Electricity generation contributes the largest proportion of CO₂ emissions compared to other types of fossil fuel use in the United States (**Table 1**). Electricity-generating plants are among the most likely initial candidates for capture, separation, and storage or reuse of CO₂ because they are predominantly large, stationary, single-point sources of emissions. Large industrial facilities, such as cement-manufacturing, ethanol, or hydrogen production plants, that produce large quantities of CO₂ as part of the industrial process are also good candidates for CO₂ capture and storage.³

Table 1. Sources for CO₂ Emissions in the United States from Combustion of Fossil Fuels

Sources	CO ₂ Emissions ^a (millions of metric tons)	Percent of Total
Electricity generation	2,108.8	41%
Transportation	1,745.0	34%
Industrial	773.2	15%
Residential	328.8	6%
Commercial	222.1	4%
Total	5,177.9	100%

Source: U.S. Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2011*, Table ES-3 (April 2013); <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html>.

a. CO₂ emissions in millions of metric tons for 2011; excludes emissions from U.S. territories.

¹ U.S. Department of Energy, National Energy Technology Laboratory, *Carbon Sequestration Through Enhanced Oil Recovery*, (March, 2008), at <http://www.netl.doe.gov/publications/factsheets/program/Prog053.pdf>.

² U.S. Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2011*, Table ES-2. The percentage refers to U.S. emissions in 2011; <http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2013-ES.pdf>.

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

This report is a brief summary of what CCS is, how it is supposed to work, why it has gained the interest and support of some Members of Congress, and what some of the challenges are to its implementation and deployment across the United States. Several other CRS reports cover different aspects of CCS in more detail, such as capture technology, challenges to siting and infrastructure, policy challenges to a comprehensive climate policy, and others. These are listed in the last section of this report, titled “Other CRS Reports.”

This report covers only CCS and not other types of carbon sequestration activities whereby CO₂ is removed from the atmosphere and stored in vegetation or soils, such as forests and agricultural lands.⁴

CO₂ Capture

The first step in CCS is to capture CO₂ at the source and produce a concentrated stream for transport and storage. Currently, three main approaches are available to capture CO₂ 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 CO₂ capture systems could operate at 85%-95% capture efficiency.⁵ The capture phase of the CCS process, however, may be 80% or more of the total costs for CCS.⁶ A detailed description and assessment of these capture technologies is provided in CRS Report R41325, *Carbon Capture: A Technology Assessment*.

Post-Combustion Capture

This process involves extracting CO₂ 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 CO₂ from flue gases. U.S. commercial electricity-generating plants currently do not capture large volumes of CO₂ 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.

Pre-Combustion Capture

This process separates CO₂ from the fuel by combining the fuel with air and/or steam to produce hydrogen for combustion and a separate CO₂ stream that could be stored. The most common technologies today use steam reforming, in which steam is employed to extract hydrogen from natural gas.⁷

⁴ For more information about carbon sequestration in forests and agricultural lands, see CRS Report RL31432, *Carbon Sequestration in Forests*, by (name redacted); CRS Report RL33898 *Climate Change: The Role of the U.S. Agriculture Sector*, by (name redacted); and CRS Report R40186 *Biochar: Examination of an Emerging Concept to Sequester Carbon*, by (name redacted). For more information about carbon exchanges between the oceans, atmosphere, and land surface, see CRS Report RL34059, *The Carbon Cycle: Implications for Climate Change and Congress*, by (name redacted).

⁵ IPCC Special Report, p. 107.

⁶ See, for example, John Deutch et al., *The Future of Coal*, Massachusetts Institute of Technology, An Interdisciplinary MIT Study, 2007, Executive Summary, p. xi.

⁷ See CRS Report R41325, *Carbon Capture: A Technology Assessment*, by (name redacted).

Oxy-Fuel Combustion Capture

This process uses oxygen instead of air for combustion and produces a flue gas that is mostly CO₂ and water, which are easily separable, after which the CO₂ can be compressed, transported, and stored. The U.S. Department of Energy's (DOE's) flagship CCS demonstration project, FutureGen, plans to retrofit an existing power unit with an oxy-fuel combustion unit.⁸

CO₂ Transport

Pipelines are the most common method for transporting CO₂ in the United States. Currently, approximately 4,100 miles of pipeline transport CO₂ in the United States, predominately to oil and gas fields, where it is used for EOR.⁹ Transporting CO₂ 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 CO₂ must be transported over large distances or overseas. Ships transport CO₂ today, but at a small scale because of limited demand. Liquefied natural gas, propane, and butane are routinely shipped by marine tankers on a large scale worldwide. Rail cars and trucks can also transport CO₂, 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 encountered. Shipping costs are unknown in any detail, however, because no large-scale CO₂ transport system (in millions of metric tons of CO₂ 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 million metric tons of CO₂ (MtCO₂)¹¹ transported per year.¹²

Even though regional CO₂ pipeline networks currently operate in the United States for enhanced EOR, developing a more expansive network for CCS could pose numerous regulatory and economic challenges. Some of these include questions about pipeline network requirements, economic regulation, utility cost recovery, regulatory classification of CO₂ itself, and pipeline safety.¹³

⁸ See CRS Report R43028, *FutureGen: A Brief History and Issues for Congress*, by (name redacted), for further discussion of FutureGen.

⁹ Kevin Bliss et al., "A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide," Interstate Oil and Gas Compact Commission, September 10, 2010, Table 3, <http://www.sseb.org/downloads/pipeline.pdf>. By comparison, nearly 500,000 miles of pipeline operate to convey natural gas and hazardous liquids in the United States.

¹⁰ IPCC Special Report, p. 181.

¹¹ One metric ton of CO₂ equivalent is written as 1 tCO₂; one million metric tons is written as 1 MtCO₂; one billion metric tons is written as 1 GtCO₂.

¹² IPCC Special Report, p. 31.

¹³ These issues are discussed in more detail in CRS Report RL33971, *Carbon Dioxide (CO₂) Pipelines for Carbon Sequestration: Emerging Policy Issues*, by (name redacted), (name redacted), and (name redacted), and CRS Report (continued...)

CO₂ Sequestration

Three main types of geological formations are being considered for carbon sequestration: (1) depleted oil and gas reservoirs, (2) deep saline reservoirs, and (3) unmineable coal seams. In each case, CO₂ would be injected in a supercritical state—a relatively dense liquid—below ground into a porous rock formation that holds or previously held fluids. When CO₂ is injected at depths greater than 800 meters in a typical reservoir, the pressure keeps the injected CO₂ in a supercritical state (dense like a liquid, fluid like a gas) and thus it is less likely to migrate out of the geological formation. Injecting CO₂ into deep geological formations uses existing technologies that have been primarily developed and used by the oil and gas industry, and that could potentially be adapted for long-term storage and monitoring of CO₂. 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 valuable experience and information for sequestering CO₂ in geological formations.¹⁴

The storage capacity for CO₂ in geological formations is potentially huge if all the sedimentary basins in the world are considered (see discussion below of storage capacity estimates for the United States).¹⁵ The suitability of any particular site, however, depends on many factors, including proximity to CO₂ sources and other reservoir-specific qualities like porosity, permeability, and potential for leakage. For CCS to succeed, it is assumed that each reservoir type would permanently store the vast majority of injected CO₂, keeping the gas isolated from the atmosphere in perpetuity.

Oil and Gas Reservoirs

Pumping CO₂ into oil and gas reservoirs to boost production (EOR) is practiced in the petroleum industry today. The United States is a world leader in this technology, and oil and gas operators inject approximately 48 MtCO₂ underground each year to help recover oil and gas resources.¹⁶ Most of the CO₂ used for EOR in the United States comes from naturally occurring geologic formations, however, not from industrial sources. Using CO₂ from industrial emitters has appeal because the costs of capture and transport from the facility could be partially offset by revenues from oil and gas production.

Carbon dioxide can be used for EOR onshore or offshore. To date, most CO₂ projects associated with EOR are onshore, with the bulk of U.S. activities in west Texas. Carbon dioxide 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.

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RL34316, *Pipelines for Carbon Dioxide (CO₂) Control: Network Needs and Cost Uncertainties*, by (name redacted) and (name redacted).

¹⁴ IPCC Special Report, p. 31.

¹⁵ 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 CO₂ storage.

¹⁶ Data from 2006. See DOE, National Energy Technology Laboratory, *Carbon Sequestration Through Enhanced Oil Recovery*, (March 2008), at <http://www.netl.doe.gov/publications/factsheets/program/Prog053.pdf>.

Advantages and Disadvantages

Depleted or abandoned oil and gas fields, especially in the United States, are considered prime candidates for CO₂ 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 for oil and gas typically have 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 CO₂ could move; and
- infrastructure and wells from oil and gas extraction may be in place and might be used for handling CO₂ storage.

Some of these features could also be disadvantages to CO₂ sequestration. Wells that penetrate from the surface to the reservoir could be conduits for CO₂ release if they are not plugged properly. Care must be taken not to overpressure the reservoir during CO₂ injection, which could fracture the caprock—the part of the formation that formed a seal to trap oil and gas—and subsequently allow CO₂ to escape. Also, shallow oil and gas fields (those less than 800 meters deep, for example) may be unsuitable because CO₂ may form a gas instead of a denser liquid and could escape to the surface more easily. In addition, oil and gas fields that are suitable for EOR may not necessarily be located near industrial sources of CO₂. Costs to construct pipelines to connect sources of CO₂ with oil and gas fields may, in part, determine whether an EOR operation using industrial sources of CO₂ is feasible.

Although the United States injects nearly 50 MtCO₂ underground each year for the purposes of EOR, that amount represents approximately 2% of the CO₂ emitted from fossil fuel electricity generation alone. The sheer volume of CO₂ envisioned for CCS as a climate mitigation option is overwhelming compared to the amount of CO₂ used for EOR. It may be that EOR will increase in the future, depending on economic, regulatory, and technical factors, and more CO₂ will be sequestered as a consequence. It is also likely that EOR would only account for a small fraction of the total amount of CO₂ injected underground in the future, even if CCS becomes a significant component in an overall scheme to substantially reduce CO₂ emissions to the atmosphere.

The In Salah and Weyburn Projects

The In Salah Project in Algeria was the world's first large-scale effort to store CO₂ in a natural gas reservoir.¹⁷ At In Salah, CO₂ was separated from the produced natural gas (the gas contains approximately 5.5% CO₂) and then reinjected into the same formation. Approximately 17 MtCO₂ were planned to be captured and stored over the lifetime of the project at a rate of slightly more than 1 Mt per year.¹⁸ Injection at In Salah ceased in 2011 and a future injection strategy is currently under review.

¹⁷ IPCC Special Report, p. 203.

¹⁸ Injection started in 2004 and was suspended in 2011 due to concerns over the integrity of the geological seal that keeps the CO₂ from leaking to the surface. The Carbon Capture and Sequestration Technologies Program at MIT, (continued...)

The Weyburn Project in south-central Canada uses CO₂ produced from a coal gasification plant in North Dakota for EOR, injecting up to 5,000 tCO₂ per day into the formation and enhancing oil recovery.¹⁹ Approximately 20 MtCO₂ are expected to remain in the formation over the lifetime of the project.²⁰

Deep Saline Reservoirs

Some rocks in sedimentary basins contain saline fluids—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.²¹

Advantages and Disadvantages

Using suitably deep saline reservoirs for CO₂ sequestration has advantages: (1) 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 CO₂; and (2) saline reservoirs have potentially the largest reservoir capacity of the three types of geologic formations.

Although deep saline reservoirs potentially have huge capacity to store CO₂, estimates of lower and upper capacities vary greatly, reflecting a higher degree of uncertainty in how to measure storage capacity.²² Actual storage capacity may have to be determined on a case-by-case basis. Estimates of storage capacity for the United States from the DOE Regional Sequestration Partnership Program are discussed below.

From estimates of the potential storage capacity in saline reservoirs, it is likely that the vast majority of CO₂ injected underground would be stored in these formations, assuming that CCS were deployed on a commercial scale across the United States. In addition to their potential capacity, deep saline reservoirs underlie large portions of the country, and could be more easily accessible to large, stationary sources of CO₂ than oil and gas reservoirs or coal seams. **Figure 1** shows broad outlines of sedimentary basins containing the deep saline reservoirs, and the locations of a variety of stationary sources of CO₂.

The DOE Regional Sequestration Partnership Program has conducted simulations, field studies, and small-scale injection projects, and is now beginning a phase of large-scale injection demonstration projects to investigate the suitability of deep saline reservoirs.²³ Because of the

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Carbon Capture and Sequestration Project Database, In Salah Fact Sheet, http://sequestration.mit.edu/tools/projects/in_salah.html.

¹⁹ IPCC Special Report, p. 204.

²⁰ MIT Carbon Capture and Sequestration Project Database, Weyburn Fact Sheet, <http://sequestration.mit.edu/tools/projects/weyburn.html>.

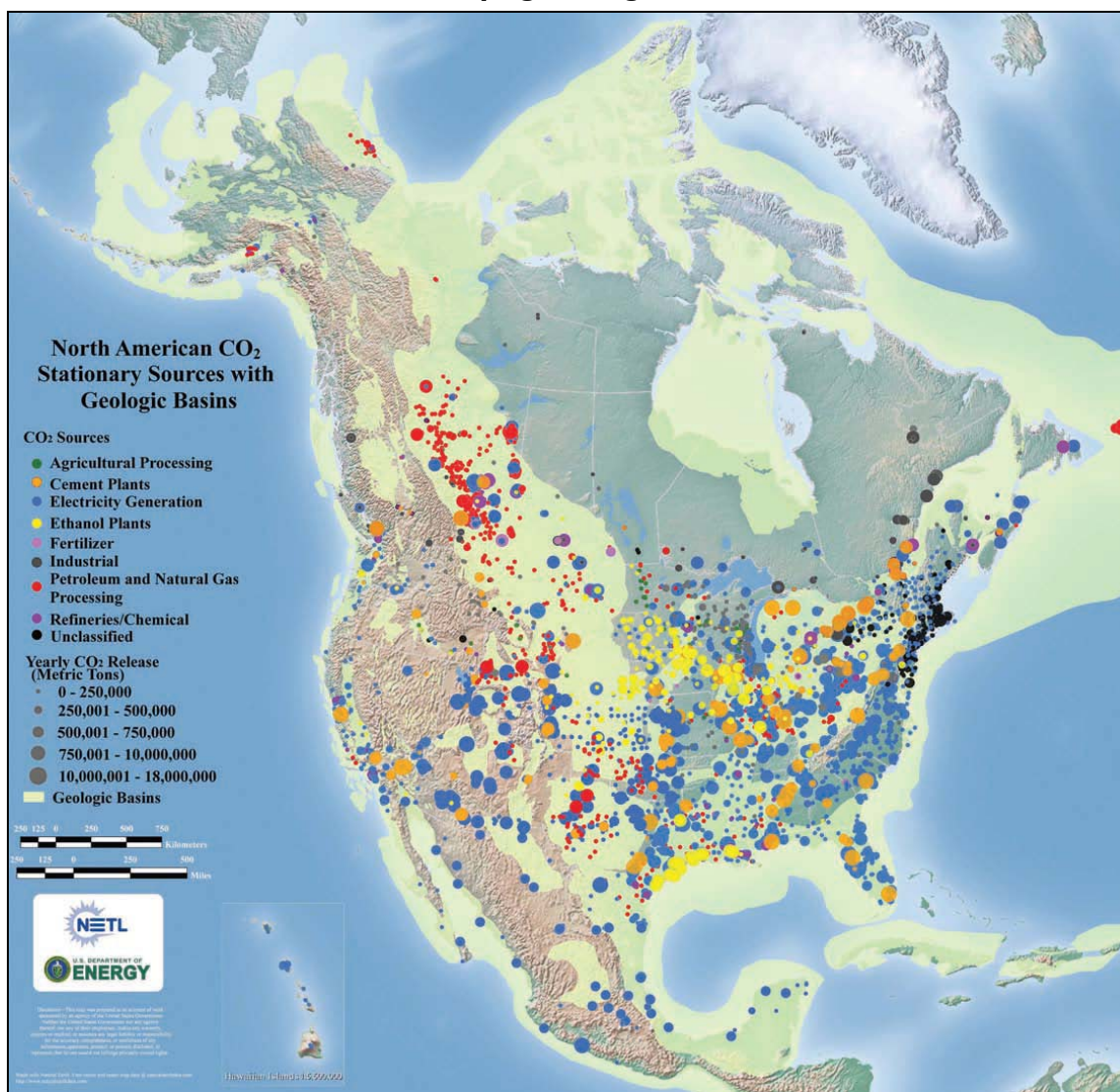
²¹ DOE Office of Fossil Energy; see <http://www.fossil.energy.gov/programs/sequestration/geologic/index.html>.

²² IPCC Special Report, p. 223.

²³ See CRS Report R42496, *Carbon Capture and Sequestration: Research, Development, and Demonstration at the U.S. Department of Energy*, by (name redacted), for more information on the DOE programs.

potentially vast amounts of CO₂ that could be sequestered, these experiments could shed light on the potential for leakage of CO₂ from the reservoir, and test the ability to detect the movement of CO₂ underground as well as to detect leaks through overlying cap rocks.

Figure 1. Stationary Sources of CO₂ in North America and Underlying Geologic Basins



Source: U.S. Department of Energy, National Energy Technology Laboratory, "2010 Carbon Sequestration Atlas of the United States and Canada, Third Edition," http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasIII/index.html.

Note: Not all geologic basins have deep saline reservoirs suitable for carbon sequestration.

In addition to the possibility of CO₂ leakage, injection of millions of tons of CO₂ will displace large volumes of brine in the deep saline reservoirs. One disadvantage is therefore the possibility that displaced brine could leak into underground sources of drinking water. Ultimately, CO₂ will likely dissolve into the brine, but that could take decades. Also, injecting large volumes of fluid into the subsurface has the potential to trigger earthquakes, especially if the CO₂ is injected into

an undetected fault. Presumably, evaluating the potential storage site prior to beginning injection will limit the potential for triggering earthquakes (also referred to as “induced seismicity”), but there is no guarantee that fluid could not migrate to faulted or fractured rocks over the course of many years and induce an earthquake. The issue of induced seismicity has been linked to the injection and disposal of produced waters from oil and gas fields.²⁴

Unlike sequestration in existing oil and gas fields, injecting into deep saline reservoirs may take place in regions of the country that have not experienced drilling activities. Public opposition may arise to activities on the surface—such as land clearing, building of new roads, transport of heavy equipment, and operation of drill rigs—but also to the concept of disposing CO₂ underground near residences and communities. There is at least one example of public opposition to CO₂ injection leading to cancellation of a project in Europe.²⁵

The Sleipner Project

The Sleipner Project in the North Sea is the first commercial-scale operation for sequestering CO₂ in a deep saline reservoir. The Sleipner project has been operating since 1996, and it injects and stores approximately 2,800 tCO₂ per day, or about 1 MtCO₂ per year.²⁶ Carbon dioxide is separated from natural gas production at the nearby Sleipner West Gas Field, compressed, and then injected 800 meters below the seabed of the North Sea into the Utsira formation, a sandstone reservoir 200-250 meters (650-820 feet) thick containing saline fluids. Monitoring has indicated the CO₂ has not leaked from the saline reservoir, and computer simulations suggest that the CO₂ will eventually dissolve into the saline water, reducing the potential for leakage in the future.

Another CO₂ sequestration project, similar to Sleipner, began in the Barents Sea in April 2008 (the Snohvit Project),²⁷ and is injecting approximately 2,000 tCO₂ per day below the seafloor. A larger project is being planned in western Australia (the Gorgon Project)²⁸ that would inject 9,000 tCO₂ per day when at full capacity (over 14 MtCO₂ per year). Similar to the Sleipner and Snohvit operations, the Gorgon plans to strip CO₂ from produced natural gas and inject it into deep saline formations for permanent storage. The Gorgon Project is scheduled to begin in 2015.

Unmineable Coal Seams

U.S. coal resources that are not mineable with current technology are those where the coal beds²⁹ are not thick enough, or are too deep, or whose structural integrity 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

²⁴ See, for example, Mike Soraghan, “Drilling Waste Disposal Risks Another Damaging Okla. Quake, Scientist Warns,” *Energywire*, April 19, 2012, <http://www.eenews.net/energywire/2012/04/19/archive/1?terms=earthquake>.

²⁵ See Paul Voosen, “Public Outcry Scuttles German Demonstration Plant,” *Greenwire*, December 6, 2011, <http://www.eenews.net/Greenwire/2011/12/06/archive/10?terms=vattenfall>.

²⁶ Carbon Capture and Sequestration Project Database, Sleipner Fact Sheet, <http://sequestration.mit.edu/tools/projects/sleipner.html>.

²⁷ Carbon Capture and Sequestration Project Database, Snohvit Fact Sheet, <http://sequestration.mit.edu/tools/projects/snohvit.html>.

²⁸ Carbon Capture and Sequestration Project Database, Gorgon Fact Sheet, <http://sequestration.mit.edu/tools/projects/gorgon.html>.

²⁹ *Coal bed* and *coal seam* are interchangeable terms.

gases are physically bound (adsorbed) to the coal. Studies indicate that CO₂ binds even more tightly to coal than methane.³⁰ 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 CO₂ injection.

Advantages and Disadvantages

Unmineable coal seam injection projects would 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 CO₂ is injected into a coal seam, it would likely remain there unless the seam is depressurized or the coal is mined. Many unmineable coal seams in the United States are located relatively near electricity-generating facilities, which could reduce the distance and cost of transporting CO₂ from large point sources to storage sites.

Not all types of coal beds are suitable for CBM extraction. Without the coal-bed methane resource, the sequestration process would be less economically attractive. However, the displaced methane would need to be combusted or captured because methane itself is a more potent greenhouse gas than CO₂. Once burned, methane produces mostly CO₂ and water.

Without ongoing commercial experience, storing CO₂ in coal seams has significant uncertainties compared to the other two types of geological storage discussed. According to IPCC, unmineable coal seams have the smallest potential capacity for storing CO₂ globally compared to oil and gas fields or deep saline formations. The latest assessment from DOE also indicates that unmineable coal seams in the United States have less potential capacity than U.S. oil and gas fields for storing CO₂. (See following discussion.) No commercial CO₂ injection and sequestration projects in coal beds are currently underway in the United States.

Geological Storage Capacity for CO₂ in the United States

DOE National Technology Laboratory Carbon Sequestration Atlas

As **Figure 1** indicates, geologic basins containing at least one of each of these three types of potential CO₂ reservoirs occur across most of the United States, in relative proximity to many large point sources of CO₂, such as fossil fuel power plants or cement plants. The DOE Regional Sequestration Partnership Program has produced estimates of the potential storage capacity for each of these types of reservoirs and published the estimates in a Carbon Sequestration Atlas. The 2012 Carbon Sequestration Atlas (fourth edition) updates the 2010 version (third edition), and a summary of the storage estimates for both editions is compared in **Table 2**.³¹

³⁰ IPCC Special Report, p. 217.

³¹ U.S. Dept. of Energy, National Energy Technology Laboratory, *2010 Carbon Sequestration Atlas of the United States and Canada*, 3rd ed. (November 2010), 160 pages. Hereinafter referred to as the 2010 Carbon Sequestration Atlas, http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasIII/2010atlasIII.pdf; and *2012 Carbon Utilization and Storage Atlas*—4th ed. (December 2012), 129 pages. Hereinafter referred to as the 2012 Carbon Sequestration Atlas, http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasIV/Atlas-IV-2012.pdf.

The Carbon Sequestration Atlas was compiled from estimates of geological storage capacity made by seven separate regional partnerships (government-industry collaborations fostered by DOE) that each produced estimates for different regions of the United States and parts of Canada. According to DOE, the department determined early in the program that addressing CO₂ mitigation from power and industrial sources regionally would be the most effective way to address differences in geology, climate, population density, infrastructure, and socioeconomic development throughout the United States.³² The Carbon Sequestration Atlas reflects some of the regional differences; for example, not all of the regional partnerships identified unmineable coal seams as potential CO₂ reservoirs. Other partnerships identified geological formations unique to their regions—such as organic-rich shales in the Illinois Basin, or flood basalts in the Columbia River Plateau—as other types of possible reservoirs for CO₂ storage.

Table 2 indicates a lower and upper range for sequestration potential in deep saline formations and for unmineable coal seams, but only a single estimate for oil and gas fields. Comparison between the 2010 and 2012 estimates indicates large changes between the two estimates for oil and gas fields and for the lower estimate for deep saline formations, but relatively small changes for the upper estimate for deep saline formations and unmineable coal seams. It is clear from the table that DOE considers estimates for oil and gas fields much better constrained by available data than for the other types of reservoirs. The amount and types of data from oil and gas fields, such as production history, and reservoir volume calculations, often represent decades of experience in the oil and gas industry. In the Carbon Sequestration Atlas, oil and gas reservoirs were assessed at the field level (i.e., on a finer scale and in more detail) than deep saline formations or unmineable coal seams, which were assessed at the basin level (i.e., at a coarser scale and in less detail).

A frequently asked question is how the estimates of storage capacity in the United States equate to years of storage, assuming a certain level of CO₂ emissions. The total lower estimate (sum of the three reservoir types) from the 2012 Carbon Sequestration Atlas shown in **Table 2** indicates the potential to store the equivalent of over 1,100 years of CO₂ emissions from electricity generation in the United States at current emission rates (2.1 billion tons per year). The total upper estimate indicates the potential for over 9,000 years of CO₂ emissions from electricity generation. These projections assume that all of the capacity could be utilized for storage, and would change if the CO₂ emissions rate changed.

The Sequestration Atlas is updated approximately every two years. Estimates of storage capacity change, often substantially, from update to update, as demonstrated in **Table 2**. The DOE Sequestration Atlas should probably be considered an evolving assessment of U.S. reservoir capacity for CO₂ storage.³³

³² 2012 Carbon Sequestration Atlas, p. 7.

³³ 2010 Carbon Sequestration Atlas, p. 139.

Table 2. Geological Sequestration Potential for the United States and Parts of Canada(billion metric tons of CO₂)

Reservoir type	Lower estimate (2010)	Lower estimate (2012)	% Change	Upper estimate (2010)	Upper estimate (2012)	% Change
Oil and gas fields	143	226	+58%	143	226	+58%
Deep saline formations	1,653	2,102	+27%	20,213	20,043	-0.8%
Unmineable coal seams	60	56	-7%	117	114	-3%
Totals	1,856	2,384	+28%	20,473	20,383	-0.04%

Source: 2010 and 2012 Carbon Sequestration Atlases.

U.S. Geological Survey National Assessment

The Energy Independence and Security Act of 2007 (EISA, P.L. 110-140) directed the Department of the Interior (DOI) to develop a single methodology for an assessment of the national potential for geologic storage of carbon dioxide. The U.S. Geological Survey (USGS) released an initial methodology in 2009. In response to external comments and reviews, the USGS revised its initial methodology in a 2010 report.³⁴ On June 26, 2013, the USGS released its assessment of geologic CO₂ storage resources across the United States, following its previously developed methodology.³⁵

The USGS obtained a mean estimate of 3,000 billion metric tons of CO₂ storage capacity below onshore areas in the United States and underlying state waters (approximately 3.5 miles from shore for most states; for Texas and the Florida Gulf of Mexico coast, the border extends about 10.3 miles from shore). The value obtained by the USGS is about 25% greater than the lower estimate from the DOE Carbon Sequestration Atlas for 2012 (**Table 2**) and is about 15% of the upper estimate from the DOE study. The USGS study differs from the DOE estimate in several ways. The USGS estimate was a geology-based examination of all sedimentary basins in the United States and underlying state waters, and was based on the same, probabilistic methodology for all basins. In contrast, the DOE estimates were derived from each of the seven regional CCS sequestration partnerships and not a single, uniform study. The DOE estimate included portions of Canada and the USGS study did not. Also, the DOE estimate included potential sequestration capacity in coal seams; the USGS study did not include coal seams.

Of the eight regions³⁶ examined in the USGS study, the Coastal Plain region accounted for two-thirds (2,000 billion metric tons) of the total storage capacity estimated, of which approximately

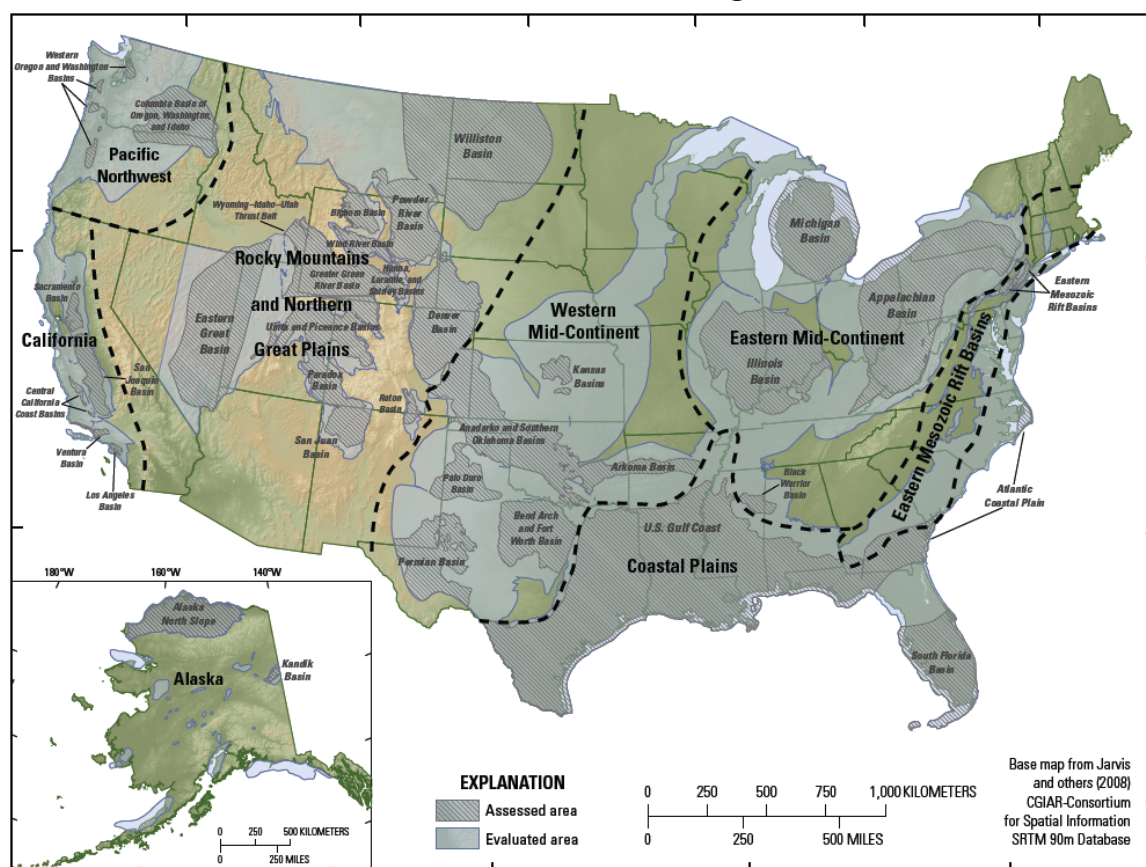
³⁴ Sean T. Brennan et al., *A Probabilistic Assessment Methodology for the Evaluation of Geologic Carbon Dioxide Storage*, USGS, Open-File Report 2010-1127, 2010.

³⁵ U.S. Geological Survey, "National Assessment of Geologic Carbon Dioxide Storage Resources—Data," June 2012, <http://pubs.usgs.gov/ds/774/>.

³⁶ These include the Pacific Northwest, California, Rocky Mountains and Northern Great Plains, Western Mid-Continent, Eastern Mid-Continent, Eastern Mesozoic Rift Basins, Coastal Plains, and Alaska.

1,800 billion metric tons of capacity is along the U.S. Gulf Coast.³⁷ (Figure 2 shows the eight regions examined in the USGS study.) The region with the next largest capacity is Alaska with 270 million metric tons, mostly along the North Slope. It is unlikely that Alaska would host a significant amount of CO₂ storage because the state lacks facilities that emit large volumes of CO₂ compared to the conterminous United States.

Figure 2. Map of the United States Showing Eight Regions Evaluated by the USGS for Potential CO₂ Storage



Source: USGS, “National Assessment of Geologic Carbon Dioxide Storage Resources—Results”, USGS Circular 1386, 2013, <http://pubs.usgs.gov/circ/1386/pdf/circular1386.pdf>.

Notes: Assessed areas are shown by the pattern, evaluated areas are bluish gray and unpatterned. Evaluated areas were not assessed for their potential for CO₂ storage. Resources in federally owned offshore areas were not assessed. Hawaii was not considered to have significant storage resources and was not assessed. Higher elevations are shown in brown and tan and lower elevations in green.

³⁷ USGS Fact Sheet 2013-3020, “National Assessment of Geologic Carbon Dioxide Storage Resources—Summary,” <http://pubs.usgs.gov/fs/2013/3020/>.

Deep Ocean Sequestration

The world's oceans contain approximately 50 times the amount of carbon stored in the atmosphere and nearly 10 times the amount stored in plants and soils.³⁸ The oceans today take up—act as a net sink for—approximately 1.7 billion metric tons of CO₂ (GtCO₂) per year. About 45% of the CO₂ released from fossil fuel combustion and land use activities during the 1990s has remained in the atmosphere, while the remainder has been taken up by the oceans, vegetation, or soils on the land surface.³⁹ Without the ocean sink, atmospheric CO₂ concentration would be increasing more rapidly. Ultimately, the oceans could store more than 90% of all the carbon released to the atmosphere by human activities, but the process takes thousands of years.⁴⁰ The ocean's capacity to absorb atmospheric CO₂ may change, however, and possibly even decrease in the future.⁴¹ Also, studies indicate that as more CO₂ enters the ocean from the atmosphere, the surface waters are becoming more acidic.⁴²

Advantages and Disadvantages

Although the surface of the ocean is becoming more concentrated with CO₂, the surface waters and the deep ocean waters generally mix very slowly, on the order of decades to centuries. Injecting CO₂ directly into the deep ocean would take advantage of the slow rate of mixing, allowing the injected CO₂ to remain sequestered until the surface and deep waters mix and CO₂ concentrations equilibrate with the atmosphere. What happens to the CO₂ would depend on how it is released into the ocean, the depth of injection, and the temperature of the seawater.

Carbon dioxide injected at depths shallower than 500 meters typically would be released as a gas, and would rise towards the surface. Most of it would dissolve into seawater if the injected CO₂ gas bubbles were small enough.⁴³ At depths below 500 meters, CO₂ can exist as a liquid in the ocean, although it is less dense than seawater. After injection below 500 meters, CO₂ would also rise, but an estimated 90% would dissolve in the first 200 meters. Below 3,000 meters in depth, CO₂ is a liquid and is denser than seawater; the injected CO₂ would sink and dissolve in the water column or possibly form a CO₂ pool or lake on the sea bottom. Some researchers have proposed injecting CO₂ into the ocean bottom sediments below depths of 3,000 meters, and immobilizing

³⁸ Christopher L. Sabine et al., "Current Status and Past Trends of the Global Carbon Cycle," in C. B. Field and M. R. Raupach, eds., *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World* (Washington, DC: Island Press, 2004), pp. 17-44.

³⁹ 2007 IPCC Working Group I Report, pp. 514-515.

⁴⁰ CO₂ forms carbonic acid when dissolved in water. Over time, the solid calcium carbonate (CaCO₃) on the seafloor will react with (neutralize) much of the carbonic acid that entered the oceans as CO₂ from the atmosphere. See David Archer et al., "Dynamics of Fossil Fuel CO₂ Neutralization by Marine CaCO₃," *Global Biogeochemical Cycles*, vol. 12, no. 2 (June 1998): pp. 259-276.

⁴¹ One study, for example, suggests that the efficiency of the ocean sink has been declining at least since 2000; see Josep G. Canadell et al., "Contributions to Accelerating Atmospheric CO₂ Growth from Economic Activity, Carbon Intensity, and Efficiency of Natural Sinks," *Proceedings of the National Academy of Sciences*, vol. 104, no. 47 (Nov. 20, 2007), pp. 18866-18870.

⁴² For more information on ocean acidification, see CRS Report R40143, *Ocean Acidification*, by (name redacted) and (name redacted).

⁴³ IPCC Special Report, p. 285.

the CO₂ as a dense liquid or solid CO₂ hydrate.⁴⁴ Deep storage in ocean bottom sediments, below 3,000 meters in depth, might potentially sequester CO₂ for thousands of years.⁴⁵

The potential for ocean storage of captured CO₂ is huge, but environmental impacts on marine ecosystems and other issues may determine whether large quantities of captured CO₂ will ultimately be stored in the oceans. Also, deep ocean storage is in a research stage, and the effects of scaling up from small research experiments, using less than 100 liters of CO₂,⁴⁶ to injecting several GtCO₂ into the deep ocean are unknown.

Injecting CO₂ into the deep ocean would change ocean chemistry, locally at first, and assuming that hundreds of GtCO₂ were injected, would eventually produce measurable changes over the entire ocean.⁴⁷ 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 and rate of the pH change and the type of organism. Actual impacts of deep sea CO₂ sequestration are largely unknown, however, because scientists know very little about deep ocean ecosystems.⁴⁸

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 tCO₂ 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.⁴⁹ A similar but smaller project with plans to release more than 5 tCO₂ 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.⁵⁰

Sequestering Under the Seabed

Deep ocean sequestration, as discussed here, is different from injecting CO₂ beneath the seabed into depleted oil and gas reservoirs or deep saline formations. The Sleipner project discussed above is an example of injection beneath the seafloor, but not injection into the ocean waters. Sequestering CO₂ under the seabed on the U.S. continental shelf would eliminate the need to negotiate with local landowners over the rights to surface land and to the pore space in the subsurface. However, it would also require developing an offshore infrastructure to transport and inject the captured CO₂, along with all the other challenges of evaluating the potential offshore reservoir, including monitoring the injected CO₂, and providing for liability and ownership of the CO₂ after injection has ceased.

⁴⁴ A CO₂ hydrate is a crystalline compound formed at high pressures and low temperatures by trapping CO₂ molecules in a cage of water molecules.

⁴⁵ 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): pp. 12291-12295.

⁴⁶ 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.

⁴⁷ IPCC Special Report, p. 279.

⁴⁸ *Ibid.*, p. 298.

⁴⁹ Virginia Gewin, "Ocean Carbon Study to Quit Hawaii," *Nature*, vol. 417 (June 27, 2002): p. 888.

⁵⁰ Jim Giles, "Norway Sinks Ocean Carbon Study," *Nature*, vol. 419 (Sept. 5, 2002): p. 6.

Mineral Carbonation

Another option for sequestering CO₂ produced by fossil fuel combustion involves converting CO₂ to solid inorganic carbonates, such as CaCO₃ (limestone), using chemical reactions. When this process occurs naturally, it is known as “weathering” and takes place over thousands or millions of years. The process can be accelerated by reacting a high concentration of CO₂ with minerals found in large quantities on the Earth’s surface, such as olivine or serpentine.⁵¹ 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.⁵²

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 CO₂ stream with the prepared minerals, and (3) separating the carbonate products and storing them in a suitable repository.

Advantages and Disadvantages

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 CO₂. Large volumes of silicate oxide minerals are needed, from 1.6 to 3.7 metric tons of silicates per tCO₂ sequestered. Thus, a large-scale mineral carbonation process needs a large mining operation to provide the reactant minerals in sufficient quantity.⁵³ Large volumes of solid material would also be produced, between 2.6 and 4.7 metric tons of materials per tCO₂ 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, estimating the amount of CO₂ that could be sequestered by this technique is difficult.

One possible type of geological reservoir for CO₂ storage—major flood basalts⁵⁴ such as those on the Columbia River Plateau—is being explored for its potential to react with CO₂ and form solid carbonates in situ (in place). Instead of mining, crushing, and milling the reactant minerals, as discussed above, CO₂ would be injected directly into the basalt formations and would react with the rock over time and at depth to theoretically form solid carbonate minerals. Large and thick formations of flood basalts occur globally, and many have characteristics—such as high porosity and permeability—that are favorable to storing CO₂. Those characteristics, combined with the tendency of basalt to react with CO₂, could result in a large-scale conversion of the gas into stable, solid minerals that would remain underground for geologic time. The DOE regional

⁵¹ Serpentine and olivine are silicate oxide minerals—combinations of the silica, oxygen, and magnesium—that react with CO₂ to form magnesium carbonates. Wollastonite, a silica oxide mineral containing calcium, reacts with CO₂ to form calcium carbonate (limestone). Magnesium and calcium carbonates are stable minerals over long time scales.

⁵² Calera, a company based in Los Gatos, CA, has developed a process for mineral carbonation that it claims will sequester CO₂ and produce solid carbonate minerals that can be used in the manufacture of building materials. The Calera process is discussed in a CRS congressional distribution (CD) memorandum, available from (name redacted) at 7-.....

⁵³ IPCC Special Report, p. 40.

⁵⁴ Flood basalts are vast expanses of solidified lava, commonly containing olivine, that erupted over large regions in several locations around the globe. In addition to the Columbia River Plateau flood basalts, other well-known flood basalts include the Deccan Traps in India and the Siberian Traps in Russia.

carbon sequestration partnerships are exploring the possibility of using Columbia River Plateau flood basalts in the Pacific Northwest for storing CO₂.⁵⁵

Current Issues and Future Challenges

A primary goal of developing and deploying CCS is to allow large industrial facilities, such as fossil fuel power plants and cement plants, to operate while reducing their CO₂ emissions by 80%-90%. Such reductions would presumably reduce the likelihood of continued climate warming from greenhouse gases by slowing the rise in atmospheric concentrations of CO₂. To achieve the overarching goal of reducing the likelihood of continued climate warming would depend, in part, on how fast and how widely CCS could be deployed throughout the economy.

The additional cost of installing CCS on CO₂-emitting facilities is a primary challenge to the adoption and deployment of CCS in the United States, especially in an environment of low natural gas prices and increasing domestic natural gas supplies. Major increases in CO₂ capture technology efficiency will likely produce the greatest relative cost savings for CCS systems, but challenges also face the transport and storage components of CCS. Ideally, storage reservoirs for CO₂ would be located close to sources, obviating the need to build a large pipeline infrastructure to deliver captured CO₂ for underground sequestration. If CCS moves to widespread implementation, however, some areas of the country may not have adequate reservoir capacity nearby, and may need to construct pipelines from sources to reservoirs. Identifying and validating sequestration sites would need to account for CO₂ pipeline costs, for example, if the economics of the sites are to be fully understood. If this is the case, there would be questions to be resolved regarding pipeline network requirements, economic regulation, utility cost recovery, regulatory classification of CO₂ itself, and pipeline safety. In addition, Congress may be called upon to address federal jurisdictional authority over CO₂ pipelines under existing law, and whether additional legislation may be necessary if a CO₂ pipeline network grows and crosses state lines.

Although DOE has identified substantial potential storage capacity for CO₂, particularly in deep saline formations, large-scale injection experiments are only beginning in the United States to test how different types of reservoirs perform during CO₂ injection. Data from the experiments will undoubtedly be crucial to future permitting and site approval regulations.

In addition, liability, ownership, and long-term stewardship for CO₂ sequestered underground are issues that would need to be resolved before CCS is deployed commercially. Some states are moving ahead with state-level geological sequestration regulations for CO₂, so federal efforts to resolve these issues at a national level would likely involve negotiations with the states.

Acceptance by the general public of large-scale deployment of CCS may be a significant challenge if the majority of CCS projects involve private land. Some of the large-scale injection tests could garner information about public acceptance, as local communities become familiar with the concept, process, and results of CO₂ injection tests. Apart from the question of how the public would accept the likely higher cost for electricity generated from plants with CCS, how a growing CCS infrastructure of pipelines, injection wells, underground reservoirs, and other facilities would be accepted by the public is as yet unknown.

⁵⁵ 2010 Carbon Sequestration Atlas, p. 30.

Other CRS Reports

CRS reports covering different aspects of CCS are listed below.

CRS Report R42496, *Carbon Capture and Sequestration: Research, Development, and Demonstration at the U.S. Department of Energy*, by (name redacted).

CRS Report R41325, *Carbon Capture: A Technology Assessment*, by (name redacted).

CRS Report R40103, *Carbon Control in the U.S. Electricity Sector: Key Implementation Uncertainties*, by (name redacted).

CRS Report RL33971, *Carbon Dioxide (CO₂) Pipelines for Carbon Sequestration: Emerging Policy Issues*, by (name redacted), (name redacted), and (name redacted).

CRS Report RL34059, *The Carbon Cycle: Implications for Climate Change and Congress*, by (name redacted).

CRS Report RL34621, *Capturing CO₂ from Coal-Fired Power Plants: Challenges for a Comprehensive Strategy*, by (name redacted) and (name redacted).

CRS Report RL34601, *Community Acceptance of Carbon Capture and Sequestration Infrastructure: Siting Challenges*, by (name redacted).

CRS Report RL34316, *Pipelines for Carbon Dioxide (CO₂) Control: Network Needs and Cost Uncertainties*, by (name redacted) and (name redacted).

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