

Feature

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What Future for Carbon Capture and Sequestration?

New technologies could reduce carbon dioxide emissions to the atmosphere while still allowing the use of fossil fuels.

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Amid the dire warnings of severe weather perturbations and globally rising temperatures, scientists, engineers, policy makers, and others are searching for ways to reduce the growing threat of climate change. There is no single solution, but the development of carbon capture and sequestration technologies, which has accelerated greatly in the last decade, may play an important role in addressing this issue.

This was not always the case. Ten years ago, the field of carbon capture and sequestration consisted of a handful of research groups working in isolation. Finding funding was difficult, as the field was not yet included in the research portfolios of traditional funding sources.

But then things began to change. In March 1992, more than 250 scientists and engineers from 23 countries gathered in Amsterdam for the First International Conference on Carbon Dioxide Removal (ICCDR-1). Researchers were surprised to learn how many of their colleagues were already seriously investigating the subject. Attendees came to that meeting as individuals, but left it as a research community whose research progress has proven extraordinary in the decade since ICCDR-1. Today, there is an interconnected international community; funding agencies, such as the U.S. Department of Energy (DOE), have established programs in carbon sequestration, and equally important, industry is analyzing and developing needed technologies. Significant challenges still lie ahead though, most pressing of which is reducing costs and developing storage options. Although the magnitude and timing of any impacts from climate change remain uncertain, there is increasing pressure to reduce greenhouse gas emissions now. A major target is CO₂ from fossil energy use.

One way to sequester carbon involves the removal of greenhouse gases directly from industrial or utility plant exhausts and subsequently storing

them in secure reservoirs. Removing CO₂ from the atmosphere by enhancing its uptake in soils and vegetation (e.g., afforestation) or in the ocean (e.g., iron fertilization) is yet another form of sequestration. Sometimes called enhancing natural sinks, the technical and political issues associated with this type of carbon sequestration have become major points of contention in the Kyoto Protocol negotiations. On the other hand, carbon capture and sequestration from large stationary sources—the focus of this paper—can be viewed as emissions avoidance and therefore probably will not require special treatment in any international climate agreement.

Emissions avoidance can also be achieved by improving energy efficiency or shifting to nonfossil energy sources (renewables and nuclear). Carbon capture and sequestration complement these traditional areas of research, particularly because the United States relies on fossil fuels for more than 85% of its energy needs, and trillions of dollars are invested in the current energy infrastructure. Transitioning away from fossil fuels use will be difficult. By reducing CO₂ emissions, however, carbon capture and sequestration allow the use of fossil energy to continue, while buying time to make the transition to other energy sources in an orderly fashion.

The technology

Detailed descriptions of carbon capture and sequestration technologies have been reported ([1–3](#)). Conceptually, they are similar to strategies used to lower SO₂, NO_x, particulates, and other pollutant emissions. One big difference, however, is that the volume of CO₂ generated is much greater than these other emissions.

So that CO₂ can be economically transported and sequestered, carbon capture prefers a relatively pure stream of the gas. Pathways for carbon capture come from three potential sources. First, several industrial processes produce highly concentrated streams of CO₂ as a byproduct. Although limited in quantity, they make good initial targets because CO₂ capture is inherent in the existing process, resulting in relatively low incremental costs. Second, power plants emit more than one-third of the CO₂ emissions worldwide, making them a prime candidate for carbon capture. Although the quantity is large, the cost of capture is significant because the CO₂ concentrations are low—typically, 3–5% in gas plants and 13–15% in coal plants. Finally, future opportunities for CO₂ sequestration may arise from producing hydrogen fuels from carbon-rich feedstocks, such as natural gas, coal, and biomass. The CO₂ byproduct would be relatively pure, and the incremental costs of carbon capture would be relatively low. The hydrogen could be used in low-temperature fuel cells and other hydrogen fuel-based technologies, but there are major costs ahead for developing a mass market and infrastructure for these new fuels.

What can be done with the large quantity of CO₂ once captured? Its commercial use would be ideal, but large-scale applications are limited. Most chemical processes using CO₂ require relatively small amounts—totals on the order of millions of tons, not the billions produced from fossil fuel combustion. Alternatively, large quantities of captured CO₂ could be stored in geological formations and the deep ocean (Table 1).

Geological sinks (see [illustration](#)) for CO₂ include deep saline formations, depleted oil and gas reservoirs, and unminable coal seams that are dispersed worldwide. Together, these can hold hundreds to thousands of gigatons of carbon (GtC), and the technology to inject CO₂ into the

ground is well established. CO₂ injection into geological formations for enhanced oil recovery (EOR), for example, is a mature technology ([4](#)). In 1998, ~60 million m³/day (annually, ~43 million metric tons) of CO₂ were injected at 67 commercial EOR projects in the United States.

Sequestration in deep saline formations or in oil and gas reservoirs is achieved by a combination of three mechanisms: displacement of the in situ fluids by CO₂, dissolution of CO₂ into the fluids, and chemical reaction of CO₂ with minerals present in the formation to form stable, solid compounds like carbonates. Displacement dominates initially, but dissolution and reaction become more important over timescales of decades and centuries. Abandoned, uneconomic coal seams are another potential storage site. CO₂ diffuses through the pore structure of coal and is physically adsorbed to it. This process is similar to the way in which activated carbon removes impurities from air or water. CO₂ can also be used to enhance the recovery of coal bed methane ([5](#)). In some cases, this can be very cost-effective or even cost-free, as the additional methane removal can offset the cost of the CO₂ storage operations.

By far, the ocean represents the largest potential sink for anthropogenic CO₂. It already contains an estimated 40,000 GtC (billion metric tons of carbon) compared with only 750 GtC in the atmosphere and 2200 GtC in the terrestrial biosphere. As a result, the amount of carbon that would double the

TABLE 1
The worldwide capacity of potential CO₂ storage reservoirs

Ocean and land-based sites together contain an enormous capacity for storage of CO₂^a. The world's oceans have by far the largest capacity for carbon storage.

Sequestration option	Worldwide capacity ^b
Ocean	1000s GtC
Deep saline formations	100s–1000s GtC
Depleted oil and gas reservoirs	100s GtC
Coal seams	10s–100s GtC
Terrestrial	10s GtC
Utilization	<1 GtC/yr

^a Worldwide total anthropogenic carbon emissions are ~7 GtC per year (1 GtC = 1 billion metric tons of carbon equivalent).

^b Orders of magnitude estimates.

atmospheric concentration would change the ocean's concentration by less than 2%. On a timescale of 1000 years, more than 80% of today's anthropogenic emissions of CO₂ will be transferred to the ocean. Discharging CO₂ directly to the ocean would accelerate this ongoing but slow natural process and would reduce both peak atmospheric CO₂ concentrations and their rate of increase (6).

A commercial success

Perhaps the most significant development has been the Sleipner Project, which started up in 1996. It is the first commercial application of emissions avoidance through the use of carbon capture and sequestration technologies.

The Sleipner oil and gas field, operated by Statoil, is located in the North Sea about 240 km off the coast of Norway. In order for natural gas drawn from the site to meet commercial specifications, its contaminant CO₂ concentration must be reduced from about 9% to 2.5%. This is a common practice at gas fields worldwide in which the CO₂ captured from the natural gas is vented to the atmosphere. At Sleipner, however, CO₂ is compressed and pumped into a 200-m-thick sandstone layer, the Utsira Formation, which lies about 1000 m below the seabed. One motivation for doing this was the Norwegian offshore carbon tax, which was then about U.S.\$50/t of CO₂ in 1991 (the tax was lowered to \$38/t on Jan. 1, 2000).

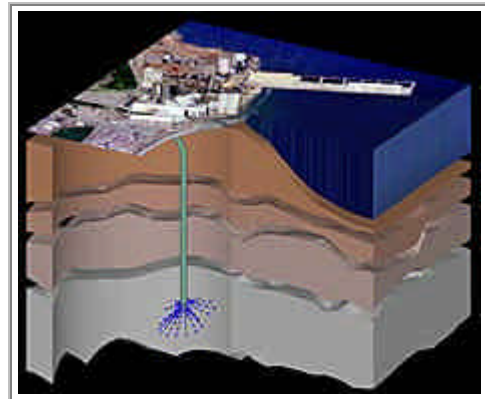
About 1 million metric tons of CO₂ (equivalent to about 3% of Norway's total annual CO₂ emissions) have been sequestered annually at Sleipner since October 1996. The incremental investment cost for sequestration was about \$80 million. Solely on the basis of carbon tax savings, the investment was paid back in about one-and-a-half years.

Today, the Saline Aquifer CO₂ Storage (SACS) Project, an international research effort, is monitoring the CO₂ injection at Sleipner, so the experience can aid future endeavors. SACS undertook a seismic survey of the injection site in October 1999. The results clearly show the "CO₂ bubble" in the aquifer. Although three years of injection is not sufficient time to make any definitive conclusions, the results are nonetheless highly encouraging. More details can be found on the IEA Gas R&D Programme Web site (www.ieagreen.org.uk).

Building a foundation

The Sleipner Project is important because it demonstrates the commercial application of carbon capture and sequestration technologies. Establishing the research foundation for developing these technologies is also critical to their long-term success.

Japan has the largest and longest running carbon capture and sequestration technologies research program. A conservative estimate is that over the past decade the government has spent more than U.S.\$50 million annually in direct expenses (not counting researcher salaries). A highlight of their program is the Research Institute of Innovative Technology for the Earth (RITE), established in July 1990 as an international research hub to promote development of innovative environmental technologies and to broaden the range of possible CO₂ sinks (see www.rite.or.jp for more information).



Captured CO₂ can be sequestered in or below the ocean as well as in geologic sinks such as deep saline formations, depleted oil and gas reservoirs, and unminable coal seams.
C Tech Development Corporation

Recently, the U.S. DOE increased its carbon capture and sequestration research budgets to U.S.\$38 million. Prior to 1998, the annual budget was ~\$1–2 million. At this early stage in the research program, DOE includes a broad range of technologies in its portfolio. Its vision for the program is to “possess the scientific understanding of carbon sequestration and to develop to the point of deployment those options that ensure environmentally acceptable sequestration to reduce anthropogenic CO₂ emissions and/or atmospheric concentrations” (see <http://cdiac2.esd.ornl.gov> and www.netl.doe.gov/products/gcc/indepth/carbseq/seq_ind.htm for more information).

Globally, the International Energy Agency (IEA) has set up an implementing agreement to establish the IEA Greenhouse Gas R&D (IEA GHG) Programme. Launched in November 1991, the IEA GHG Programme has 17 member countries and 7 industrial sponsors. The international collaboration aims to identify and evaluate technologies for reducing emissions of greenhouse gases arising from fossil fuel use. Its primary technical focus is carbon capture and sequestration (see www.ieagreen.org.uk for more information).

Successors to ICCDR-1 are held every two years as a venue for the research community to present and discuss their findings. The name was changed after ICCDR-3 in 1996 to Greenhouse Gas Control Technologies (GHGT), and the IEA GHG Programme was named the sanctioning body for the meeting. Papers from this series of meetings are an excellent set of technical references ([7–10](#)). GHGT-6 will be held in Kyoto, October 2002, with RITE

as the conference organizer.

Technical sessions on carbon capture and sequestration are frequently included as a part of meetings sponsored by the American Chemical Society, American Society of Mechanical Engineers, American Institute of Chemical Engineers, American Geophysical Union, and Air & Waste Management Association. In May 2001, the First National Conference on Carbon Sequestration will be held under the sponsorship of DOE's National Energy Technology Laboratory.

The final element of the foundation for moving the technology forward is industry's involvement. Several major companies have initiated research projects. Last year, seven energy companies (BP, Chevron, Norsk Hydro, Shell, Statoil, Suncor, and Texaco) formed a joint industry project called the CO₂ Capture Project. Its aim is to develop breakthrough technologies that reduce the cost of CO₂ capture and storage in geologic formations. The budget for the three-year technology development phase of this project totals ~\$15–20 million (see www.co2captureproject.org for more information).

Reducing costs

Building this foundation to address the challenges of developing carbon capture and sequestration technologies is a necessary first step. Reducing costs is another challenge.

Carbon capture and sequestration costs can be considered in terms of four components: capture, compression, transport, and injection. These costs depend on many factors, including the source CO₂, transportation distance, and the type and characteristics of the sequestration reservoir. Capturing and sequestering 90% of the CO₂ from a power plant would add 2¢/kWh_e to the busbar costs (see reference ([11](#)) for a more detailed analysis), with 75–80% of this cost attributable to capture and compression processes. At this price, carbon sequestration competes favorably with the current costs of renewable and nuclear energy. This competitive price position, however, could change in the future. Moreover, it is not clear what abatement costs society is willing to bear to address climate change. High priority is therefore given to reducing these costs. As discussed later, there are good reasons to be optimistic about achieving significant cost reductions.

Capturing CO₂ from a power plant is already a commercial process. More than a dozen capture plants exist worldwide, with the CO₂ being sold into commercial markets. Presently, all commercial CO₂ capture plants use processes based on chemical absorption with a monoethanolamine (MEA) solvent. MEA was developed more than 60 years ago as a general, nonselective solvent to remove acid gases, such as CO₂ and H₂S, from natural gas streams. For CO₂ capture from flue gas, the process was modified to incorporate inhibitors that resist solvent degradation and equipment corrosion; also, solvent strength is kept relatively low, resulting in

large equipment sizes and high-regeneration energy requirements.

Until recently, no efforts were made to adapt and optimize this process for carbon sequestration, although such efforts could produce significant energy and cost savings. The development of a membrane contactor (12) is a good example of the type of advances that are possible. This technology reduces the size of the absorber and stripper units by 65% and lowers the reboiler duty and solvent loss. By making the process equipment more tolerant to the solvent, this technology enables additional solvent optimization, which should further reduce energy requirements and associated costs.

In addition, new processes and approaches are under investigation. Technologies such as membrane separation, cryogenic fractionation, and adsorption using molecular sieves to capture the CO₂ from the flue gas of a power plant have been considered, but they are even less energy-efficient and more expensive than chemical absorption, partly because of the very low CO₂ partial pressure in the flue gas.

Two alternative strategies to these postcombustion approaches are also under active consideration: “oxyfuel” and “precombustion”. The major component of flue gas is nitrogen from the air feed. If there were no nitrogen, CO₂ capture from flue gas would be greatly simplified. In the oxyfuel approach, the power plant is fed oxygen produced by an air separation plant instead of air. Combustion with oxygen, however, yields temperatures too large for today’s plant construction materials, so some flue gas must be recycled to moderate the temperature. Applying this process is easier for steam than for gas turbine plants. In the former, relatively straightforward boiler modifications are required; in the latter, much more complex gas turbine design changes are required.

The postcombustion approaches in use today require cleanup of NO_x and SO₂ before CO₂ separation. The oxyfuel route does not. If the carbon sinks tolerate NO_x and SO₂, it would be possible to eliminate separate control steps and sequester NO_x and SO₂ along with CO₂, resulting in a zero-emission power plant.

An example of the precombustion route is an integrated coal gasification combined cycle plant. Coal is gasified to form synthesis gas (syngas) of CO and H₂. The gas then undergoes the water–gas shift, in which CO reacts with steam to form CO₂ and H₂. The CO₂ is removed, and the H₂ is sent to a gas turbine combined cycle. This approach allows for a CO₂ removal process (e.g., a physical solvent process like Selexsol) that is much less energy-intensive than the MEA process because capture takes place from the high-pressure syngas as opposed to the atmospheric pressure flue gas. A similar process is available for natural gas, wherein syngas is formed by steam reforming of methane.

The precombustion route opens up opportunities for “polygeneration”, in which, besides electricity and CO₂, additional products are produced. For example, instead of sending H₂ to a turbine, it can be used to fuel a hydrogen economy. Syngas, moreover, is an excellent feedstock for many chemical processes.

Storage options

The research community must also demonstrate that the various storage reservoirs proposed for carbon sequestration are effective, safe, and environmentally sound. Better understanding of the long-term fate of CO₂ in storage reservoirs is therefore an important research topic.

Although not providing perfect containment, initial analysis suggests that both geologic and oceanic storage of CO₂ can be very effective. Because the ocean and atmosphere are constantly exchanging CO₂, some fraction of that which is injected into the ocean will eventually find its way back to the atmosphere—about 15–20% will escape over a period of hundreds of years, with the rest remaining in the ocean indefinitely. For geologic reservoirs, expected residence times are long—at least thousands of years. If the CO₂ reacts underground to form carbonate minerals, storage could be even more effective.

Environmental impacts may be the most significant factor in determining the acceptability of ocean storage. Because most CO₂ emitted to the atmosphere today later ends up in the ocean, long-term (decades to centuries) environmental effects will be similar, regardless of whether CO₂ is emitted by plants to the atmosphere or captured and directly injected into the ocean. However, direct injection does have some unique environmental impacts near the injection point. Already, it is known that pH drops because of reaction of CO₂ with seawater. This principally affects nonswimming marine organisms (e.g., zooplankton, bacteria, and benthos) residing at depths of about 1000 m or greater. The magnitude of the impact depends on the extent of pH change and the duration of exposure. Fortunately, this impact can be controlled by the method of CO₂ injection. Data suggest that pH change effects can be completely avoided if the injection technique disperses the CO₂ as it dissolves into seawater.

For geologic sequestration, safety is of greater concern than environmental impacts. Although the geologic formations under consideration are not generally thought of as sensitive ecosystems, some do exist near populated areas. CO₂ is not toxic or flammable, but it is heavier than air and can cause suffocation if present at high enough concentrations. The gas, however, is routinely handled safely in large quantities every day by industry. For the technology to be acceptable, safe practices must similarly be developed for CO₂ sequestration. The mechanisms for potential leaks, both large and small, must be understood, and dangerous situations must be avoided or safely

handled.

The best way to investigate the above issues is to conduct demonstration projects that incorporate an extensive program of monitoring. This should provide the data needed for identifying the characteristics of a good storage reservoir, predicting the long-term fate of sequestered CO₂, and measuring environmental impacts. These types of demonstration projects, however, can be expensive—even the smallest ones cost tens of millions of dollars. This is why taking advantage of projects where CO₂ is already being injected is so critical. One example is the SACS Project, which is monitoring the Sleipner field. Other projects envision monitoring sequestration in active oil fields, where the injected CO₂ can be used for enhanced oil recovery to help offset costs.

Possibilities and limitations

The research community must reach out to policy makers, the environmental community, and the general public and educate them on the possibilities and limitations of this approach. Carbon capture and sequestration are not an alternative to better energy efficiency or increased use of noncarbon energy sources. They are, however, an important complement, because if more technological options are available, there will be less difficulty in addressing climate change. In addition, lower associated costs and practical solutions are found in a mix of technologies, with those adopted depending on local circumstances.

Although the need for carbon capture and sequestration technologies is evident, the magnitude of their role is hard to predict. They are, however, uniquely compatible with today's fossil energy infrastructure and can help smooth the transition from today's fossil-based energy system to a more climate-friendly future energy system. These and other advanced, innovative technologies are becoming increasingly important to achieve reductions in greenhouse gas emissions at an affordable price.

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