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# The Case for Carbon Capture and Storage

*The technology is advancing rapidly; now the government needs to lead the push for deployment.*

Human activity spills about 25 billion tons of carbon dioxide ($CO_2$) into the atmosphere every year, building up the levels of greenhouse gases that bring us ever closer to dangerous interference with Earth's climate system. The world's forests take up about 2 or 3 billion tons of that output annually, and the ocean absorbs 7 billion tons. Experts estimate that another 5 to 10 billion tons of this greenhouse gas—as much as 40% of human-made $CO_2$—could be removed from the atmosphere and tucked safely away.

Advancing the technologies needed to capture and store $CO_2$ is a sensible strategy. In addition to increasing renewable energy and promoting energy efficiency and conservation, the strategy of advancing $CO_2$ capture and storage (CCS) can be easily understood by all Americans who acknowledge that even though fossil fuels will be needed for a long time to come, the U.S. government at some point must confront the climate change problem by setting limits on $CO_2$ emissions.

Capturing and storing $CO_2$ is a cost-competitive and safe way to achieve large-scale reductions in emissions. CCS technology offers a unique opportunity to reconcile limits on $CO_2$ emissions with society's fossil fuel–dominated energy infrastructure. In order to continue using the United States' vast domestic coal resources in a world where $CO_2$ must be constrained, the country will need to rely on technology that can seize $CO_2$ generated from coal-fired power plants and store it in geologic formations underground. However, the integration and scaling up of existing technologies to capture, transport, and store $CO_2$ emitted from a full-scale power plant have not yet been demonstrated. The technical feasibility of integrating a complete CCS system with a commercial-scale power plant is not in doubt, but it is necessary to build up experience by advancing early deployment.

In addition to the environmental benefits, more aggressive support of CCS technology is critical to maintaining U.S.

For more than 20 years, San Francisco Bay area artist and photographer David Maisel has photographed terrains from low flying planes, creating images that are both beautiful and disturbing at the same time. His most recent project, a sample of which is reproduced here, is entitled *Terminal Mirage* and focuses on and around the Great Salt Lake in northwestern Utah. In his work, Maisel intentionally obscures the function, location and scale of his subject in order to create a tension between the aesthetic appeal of the image and the often disturbing narrative of the subject matter.

For more information on David Maisel, his work, and upcoming exhibitions, please visit www.davidmaisel.com

leadership and competitiveness in both CCS and global energy-technology markets. The United States has played a leading role in nearly all R&D related to the use of fossil fuels and has always had particular expertise in coal-based power-production technologies. Yet despite the great potential of CCS, the U.S. government is not investing in it aggressively. The current administration emphasizes the importance of advanced technologies, including CCS, in addressing climate change, but is not effectively promoting its demonstration and deployment. U.S. industry is already beginning to lose ground, because the handful of existing large-scale CCS projects are not in the United States.

The private sector has shown substantial interest in CCS and has begun investing in development and demonstration projects. But progress will be slow without government-created incentives. The challenge for the government is to harness the private sector's interest by developing policies that reward investment in and early deployment of CCS systems.

**The state of the art**

Large stationary sources of $CO_2$ are good candidates for CCS. Power plants are the largest emitters, generating 29% of $CO_2$ emissions. The gas also can be captured from some large-scale industrial processes that release lots of $CO_2$, including the production of iron, steel, cement, chemicals, and pulp; oil refining; natural gas processing; and synthetic fuels production. Small nonpoint sources of $CO_2$, including emissions from vehicles, agriculture, and heating systems in buildings, are not good candidates for CCS because there currently is no way to capture the $CO_2$ from these dispersed sources.

A complete CCS system relies on three technological components: capture, transport, and storage. Technologies that are used commercially in other sectors are available for each of these components. $CO_2$ capture technology is already widely used in ammonia production and other industrial manufacturing processes, as well as oil refining and gas processing. $CO_2$ gas has been transported through pipelines and injected underground for decades, most notably in west Texas, where it is used to enhance oil recovery from wells in which production is declining. In addition, some 3 to 4 million tons of $CO_2$ per year is stored underground at several locations in other countries.

$CO_2$ capture technologies can be divided into three categories: post-combustion or "end-of-pipe" $CO_2$ capture, relying on chemical or physical absorption of $CO_2$; pre-combustion $CO_2$ capture technologies that separate $CO_2$ from a syngas fuel (produced from coal, oil, or natural gas) before the fuel is burned; and oxyfuel combustion, in which oxygen instead of air is introduced during the combustion process to produce a relatively pure stream of $CO_2$ emissions.

Of these options, pre-combustion capture is currently the most efficient and therefore the cheapest. In the case of coal-fired power plants, however, pre-combustion capture can be applied only when coal gasification technology is employed, such as in integrated gasification combined-cycle coal-fired power plants.

Once the $CO_2$ is separated and captured, it must be compressed to reduce the volume of gas for transportation to an appropriate storage location. Compressing gas uses a lot of energy, so this part of the CCS system adds to the overall implementation costs. $CO_2$ can be best transported by pipeline or ship. Ships are cost-effective only if the $CO_2$ must be moved more than 1,000 miles or so. A network of $CO_2$ pipelines is already being used in several areas of the United States for enhanced oil recovery, so building and operating $CO_2$ pipelines is unlikely to pose technical or safety challenges. But regional siting limitations are possible.

Three alternative approaches to storing $CO_2$ in a reservoir other than the atmosphere have been proposed: geological storage, storage in the ocean, or aboveground land storage. Geologic storage is currently the most promising approach. It involves direct injection of $CO_2$ into underground geologic formations, including depleted oil and gas reservoirs, unminable coal seams, and deep saline aquifers. Public opposition to the idea of injecting $CO_2$ directly into the deep ocean has prevented some research on this option, despite the ocean's natural capacity to store most of the $CO_2$ currently emitted into the atmosphere. The potential of aboveground land storage is limited by the impermanence and short (decade-long) time-scale of carbon storage in biomass and the slow reaction rates associated with the formation of carbonate minerals.

The oil industry has substantial commercial experience with $CO_2$ injection to enhance oil production. That experience provides support for exploiting the many opportunities for coupled enhanced oil recovery/$CO_2$ storage. At Weyburn in Saskatchewan, $CO_2$ has been injected underground since 2000 for the dual purpose of enhancing oil recovery and storing $CO_2$. Interest in storing $CO_2$ in other underground reservoirs, including aquifers, has been increasing rapidly. Both the private and public sectors have contributed support to a handful of underground $CO_2$ storage projects that are not intended to enhance oil recovery. At Sleipner in the North Sea, the Norwegian national oil company Statoil has been injecting $CO_2$ separated out from the production of natural gas into a saline aquifer since 1996. In the fall of 2004, at In Salah in Algeria, BP similarly began injecting $CO_2$ separated from the extracted natural gas back into the gas reservoir. Several other projects of even greater scale than these existing ones are planned in Australia, Germany, and the United States in the next few years.

DAVID MAISEL, *Terminal Mirage #253-4*, C-print, 48 x 48 inches, 2003.

**Risks and uncertainties**

The dominant safety concern about CCS is potential leaks, both slow and rapid. Gradual and dispersed leaks will have very different effects than episodic and isolated ones. The most frightening scenario would be a large, sudden, catastrophic leak. This kind of leak could be caused by a well blowout or pipeline rupture. A sudden leak also could result from a slow leak if the $CO_2$ is temporarily confined in the near-surface environment and then abruptly released.

$CO_2$ is benign and nontoxic at low concentrations. But at high concentrations it can cause asphyxiation, primarily by displacing oxygen. The most noteworthy natural example of a catastrophic $CO_2$ release was in the deep tropical Lake Nyos in Cameroon in 1986. Lake water that was gradually saturated with $CO_2$ from volcanic vents suddenly turned over and released a huge amount of the gas; the $CO_2$ cloud killed 1,700 people in a nearby village. An event like this can occur only in deep tropical lakes with irregular turnover, but it is conceivable that leaking $CO_2$ could infiltrate caverns at shallow depths and then suddenly be vented to the atmosphere. $CO_2$ is denser than air, so when released it tends to accumulate in shallow depressions. This increases the risk in confined spaces close to the ground, such as buildings and tents, more than it does in open terrain, where $CO_2$ will diffuse quickly into the air.

Before any $CO_2$ storage project will be allowed to begin, it will have to be demonstrated to regulators that the likelihood of rapid leakage is negligible and that any gradual leakage will be extremely slow. Also, monitoring and verification procedures will be able to detect potential leaks.

In addition to undermining the purpose of a storage project, $CO_2$ leakage from an underground reservoir into the atmosphere could have local effects: ground and water displacement, groundwater contamination, and biological interactions. Monitoring technology that can measure $CO_2$ concentrations in and around a storage location to verify effective containment of the gas has demonstrated that leakage back to the atmosphere has not been a problem in current $CO_2$ storage projects.

Leakage from a naturally occurring underground reservoir of $CO_2$ in Mammoth Mountain, California, provides some perspective on the potential environmental effects. The leaking led to the death of plants, soil acidification, increased mobility of heavy metals, and at least one human fatality. This site is a useful natural analog for understanding potential leakage risks, but Mammoth Mountain is situated in a seismically active area, unlike the sedimentary basins where engineered $CO_2$ storage would take place. Still, we should be wary of undue optimism and continue to question the safety of artificial underground $CO_2$ storage. Given potential risks and uncertainties, the implementation of effective measurement, monitoring, and verification tools and procedures will play a critical role in managing the potential leakage risks of all $CO_2$ storage projects.

Because of the high degree of heterogeneity among different geologic formations, the current set of $CO_2$ storage projects is not necessarily representative of other likely storage locations. More demonstration projects are needed in different geologic areas. Some preliminary work has been done to understand the global distribution of appropriate underground reservoirs. But the regional availability of storage locations has not yet been well characterized, although this will be critical in determining the extent of possible CCS deployment throughout the world. Significant expansion of the number of $CO_2$ storage projects and continued research on the mobility of the injected $CO_2$ (and the risks associated with its leakage) should be high priorities.

To reduce the risks associated with $CO_2$ leaks, it is possible to choose "smart storage" sites first. Aquifers and depleted oil and gas fields under the North Sea, for example, provide a relatively safe opportunity for initial large-scale deployment. Risks associated with leakage from geologic reservoirs beneath the ocean floor are less than risks of leakage from reservoirs under land, because if the containment falters, the dissipating $CO_2$ would diffuse into the ocean rather than reentering the atmosphere.

The United States is doing little to advance the deployment of CCS technologies, but the government did spend about $75 million in 2004 on R&D. The primary goal of the core CCS R&D program is to support technological developments that will reduce implementation costs. In addition, the Department of Energy supports—with a $100 million budget over four years—a Regional Sequestration Partnership program that stimulates region-specific research designed to determine the most suitable CCS technologies, regulations, and infrastructures, as well as to assess best management practices and public opinion issues. It will also develop a database on potential geologic storage sites. The purpose of this partnership is to bring CCS technology from the laboratory to the field-testing and validation stage.

The United States has also initiated one large-scale demonstration project, FutureGen, to investigate the technical feasibility and economic viability of integrating coal gasification technology with CCS. FutureGen, launched in 2003 with a projected budget of some $1 billion, was supposed to be the first demonstration of a commercial-scale coal-fired power plant that captures and stores $CO_2$. But no site has yet been selected, and funding for the construction phase has not been allocated. FutureGen's future is uncertain.

Thus, although the government is supporting some CCS R&D and has initiated planning of one large-scale CCS demonstration project, none of the current efforts provide the incentives necessary for the private sector to begin deployment.

Economics will largely determine whether CCS can compete with carbon-mitigating energy alternatives. Despite the extensive commercial experience with technological components in other applications, minimal experience in integrating capture, transport, and storage into one system so far means that current cost projections are quite uncertain.

For power plants using modern coal gasification combined-cycle technology or a natural gas combined cycle, the costs of capturing, transporting, and storing carbon dioxide are estimated at about \$20 to \$25 per metric ton of $CO_2$. For plants using traditional pulverized coal steam technology, these costs could double.

$CO_2$ capture technology is itself energy-intensive and requires a substantial share of the electricity generated. Accounting for the corresponding power plant efficiency reduction (up to 30%) by expressing costs in dollars per ton of $CO_2$ avoided, the costs of CCS in power plants range from \$25 to \$70 per ton of $CO_2$ avoided. These figures imply an additional 1or 2 cents per kilowatt hour (kWh) for new coal gasification power plants, which have a baseline cost of about 4 cents per kWh.

Currently, these cost estimates are dominated by the cost of capture (including compression). If transport distances are less than a few hundred miles, the cost of capture constitutes about 80% of the total costs. The broad range of current cost estimates for CCS systems results from a high degree of variability in site-specific considerations. Among these are the particular power plant technology, transportation distance, and storage site characteristics. For all power plant alternatives and components, costs are expected to decline as new technologies are developed and as more knowledge is gained from demonstration projects and early deployment efforts.

But if the United States does not step up efforts to advance CCS deployment, the cost reductions from learning by doing will not emerge soon. In addition, growing experience and expertise in other countries could reduce U.S. competitiveness in CCS.

European leadership in CCS deployment began in 1996, when the Norwegian government instituted a tax on $CO_2$ emissions equivalent to about \$50 per ton of carbon avoided. This tax motivated Statoil to capture the $CO_2$ emitted from its Sleipner oil and gas field and inject it into an underground aquifer. More recently, the British government has taken the lead on CCS deployment by announcing ?40 million to support $CO_2$ storage in depleting North Sea oil and gas fields. This effort was initiated a month before the July 2005 G8 summit, where its chairman, British Prime Minister Tony Blair, advocated increased governmental support for developing carbon-abatement technology as a critical part of confronting climate change.

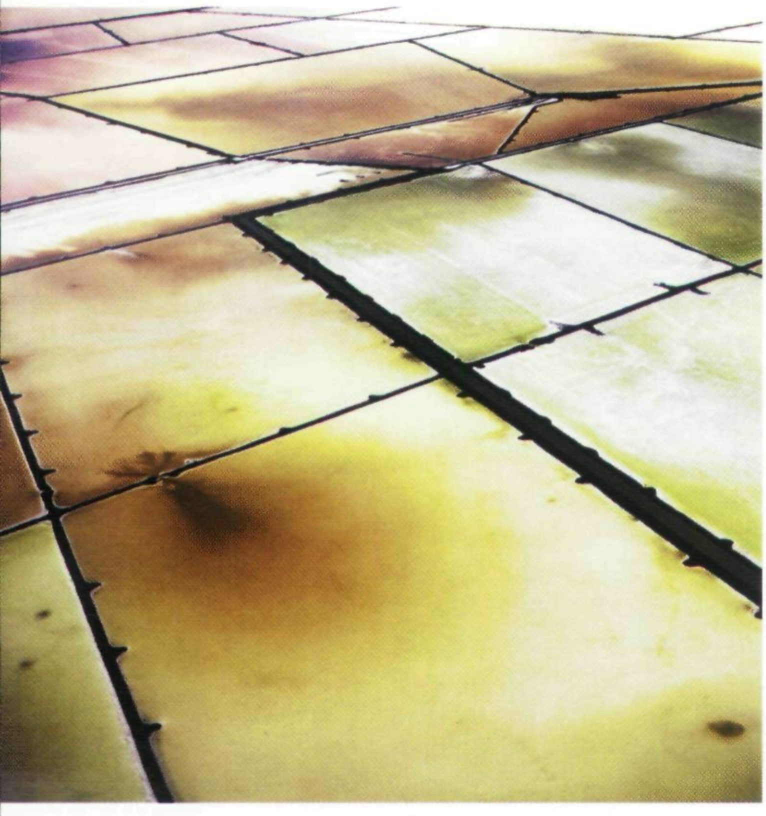
Injecting $CO_2$ to enhance oil and gas recovery in the North Sea is not commercially viable without government support. But given the high costs of decommissioning these production wells and the economic benefits associated with retaining jobs and extracting more oil and gas, the British have recognized an opportunity. By providing support for $CO_2$ storage, the British are simultaneously advancing CCS technology, potentially offsetting decades of European $CO_2$ emissions, and extending production of the oil and gas fields for several more decades. Opportunities for early deployment of CCS also exist for other European nations with declining production of oil and gas wells in the reservoirs beneath the North Sea. Denmark, the Netherlands, and Norway may initiate programs similar to those of the British soon.

**ECONOMICS WILL DETERMINE WHETHER CCS CAN COMPETE WITH CARBON-MITIGATING ENERGY ALTERNATIVES.**

Climate policies being implemented and refined in the European Union (EU) and other countries that signed the Kyoto agreement to reduce greenhouse gas emissions provide some incentive for CCS, so more large-scale CCS projects are imminent. The practical experience obtained through this deployment will elevate the countries and companies involved in these projects to leaders in developing, improving, and exporting CCS technologies.

The United States has recognized efforts elsewhere in the world to advance CCS, so in 2003 it initiated the Carbon Sequestration Leadership Forum , a venue for international collaboration among its 17 member states. It facilitates joint projects and communication about the latest developments in CCS technology. But the United States could be doing a lot more in the international arena than simply facilitating communication. The stakes are too high not to adopt aggressive strategies for domestic CCS deployment as well.

In the absence of large-scale domestic CCS implementation, the United States is likely to lose its current leadership position in frontier fossil-fuel expertise. Even if no meaningful climate policy materializes in the United States in the near term, the CCS market will grow. If the United States wants to maintain a leadership role in CCS technology, it will need to begin deployment soon.



DAVID MAISEL, *Terminal Mirage #236-1*, C-print, 48 x 48 inches, 2003.

**Balancing R&D, demonstration, and deployment**

CCS is only one set of technologies with the potential to contribute to stabilizing $CO_2$ emissions. Two seemingly polar opinions predominate about technology for reducing emissions. One side argues persuasively that because humanity already possesses the technological know-how to begin solving the climate problem, the focus should be on implementing all existing methods and technologies. The other side argues that because we have not yet developed sufficient non–$CO_2$-emitting energy technologies, what we need are revolutionary changes in energy production.

But in fact this is a misleading dichotomy. It exists largely because different time scales implicit in each view have not been appropriately reconciled and correctly associated with corresponding parts of the $CO_2$ concentration stabilization path. During the first 50 years of $CO_2$ stabilization, emissions need only be maintained at their current level. Existing technologies can be implemented to achieve this initial part of the stabilization path. Beyond 50 years, atmospheric $CO_2$ stabilization requires steep emission reductions. We do not yet have the technologies to achieve this, so undertaking intensive energy R&D is a necessity.

Thus, the view that we have a portfolio of existing technologies that allow us to start today on the path toward stabilization actually complements the view that new technologies will be required to maintain that stabilization path beyond 50 years. The critical question now is not whether to combine R&D, demonstration, and deployment efforts, but rather how to balance limited resources among these.

Interestingly, technologies associated with CCS can fit comfortably into the spectrum of opinion about how to achieve reduced emissions. Three of the 15 potential changes involving existing technology proposed by Stephen Pacala and Robert Socolow in a 2004 Science article involve capturing $CO_2$ and storing it in underground formations. Geologic storage of carbon released from fossil-fuelled energy production is one of the potential carbon-emission–free primary energy sources identified in a 2002 *Science* article by Martin Hoffert et al. as needing R&D to overcome limiting deficiencies in existing technology. CCS is thus a set of technologies and concepts at varying stages of readiness.

Although the federal government should continue and increase its support for R&D to improve CCS technology and identify the best storage sites, the most critical and immediate requirement for advancing CCS technology is incentives for companies to begin early deployment. Private-sector interest in CCS is growing rapidly, demonstrating an increasing acceptance of the idea that CCS technologies are going to play a role in future energy production. Many companies in the oil and gas industry are already beginning to invest in and prepare for CCS deployment. The most recent came in June 2005, when BP and several industry partners announced plans to build the world's first integrated commercial-scale power plant with $CO_2$ capture and storage. The project involves a 350-megawatt power plant in Scotland, from which $CO_2$ will be captured and then transported to the North Sea, to be injected into underground reservoirs for storage plus enhanced oil recovery.

Most current industry projects receive some government support. The most recently initiated $CO_2$ storage project, in In Salah, Algeria, is a joint venture with BP, Sonatrach (the Algerian national energy company), and Statoil. The Sleipner $CO_2$ storage project has some support from the EU, and the Weyburn project is funded by the Canadian government. Because of the level of interest and the fact that there is so much to learn, various organizations have been involved in many of the existing projects.

In the United States there are similar opportunities. But without a regulatory framework to provide incentives for reducing $CO_2$ emissions, companies remain hesitant. The high cost of CCS deployment, as well as the large scale and the complex integration of CCS technologies with existing energy infrastructures, means that the private sector will not act without clear government rules and support. Just as it has in Europe, U.S. government-coordinated demonstration or early-deployment CCS projects with commercially motivated enhanced oil recovery would provide a cost-effective early opportunity for advancing CCS.

Unlike other emerging energy technologies that would compete with the existing fossil fuel infrastructure, CCS provides a way for fossil fuel industries to reconcile continued use of these fuels with climate change mitigation. But to guide the fossil fuel industries toward CCS, the government must set limits on $CO_2$ emissions. The fossil fuel industries have evolved and grown under the assumption that there is no cost associated with emitting $CO_2$. Government limits will force them to reorder their priorities and investments.

There are various approaches to regulating $CO_2$, but the broadest support exists for a cap-and-trade system. This approach was recently endorsed by the National Commission on Energy Policy and is also the approach incorporated into the proposed McCain-Lieberman Climate Stewardship Act.

**THE MOST CRITICAL AND IMMEDIATE REQUIREMENT FOR ADVANCING CCS TECHNOLOGY IS INCENTIVES FOR COMPANIES TO BEGIN EARLY DEPLOYMENT.**

Incentives for early deployment are the most critical requirements for advancing CCS. Given the increasing technical feasibility of CCS, the country needs experience at the commercial scale and the associated learning by doing as soon as possible. Right now, early deployment is more important than widespread deployment, because much will be learned from an initial set of full-scale CCS operations, and those lessons will influence more advanced deployment.

Demonstration is a critical component of technology innovation, so increased funding for demonstration projects is essential to the advancement of CCS technology. Large-scale demonstration projects should be government/industry partnerships, with seed money coming from government and substantial contributions coming from participating companies. The goals and parameters of each project, as well as the mechanisms for learning from the experience and evaluation methods, should be developed jointly by government and industry. Companies should take the lead on implementation because of their expertise in large-scale projects.

The increasingly precarious FutureGen project was developed to be the first fully integrated demonstration effort, but its slow progress and uncertain future have been frustrating. This discouraging history suggests that earmarking such a large proportion of the government's total CCS funds for one ambitious commercial-scale power plant is not an efficient use of resources. The demonstration of capture technology in existing power plants or the integration of capture technology in the design of several of the new power plants built in the next few years could be a cheaper way to achieve operational proficiency and to realize overall CCS cost reductions through learning by doing.

In addition to demonstrating $CO_2$ capture technology in commercial-scale power plants, we need more large-scale $CO_2$ storage demonstration projects in a diverse set of locations in order to get experience in geologically heterogeneous reservoirs, both in the United States and elsewhere. The lessons derived from these additional projects would strengthen the case for geologic storage and provide additional information on safety and environmental concerns.

Detailed regional maps of storage potential need to be developed throughout the world. Geologic assessments are needed particularly in China, India, and other coal-rich developing countries. Their rapid economic growth is associated with dramatic increases in $CO_2$ emissions, and the potential for CCS in these countries has not yet been assessed systematically. The level of U.S. action on CCS technology will affect global understanding of the potential for CCS in developed and developing countries and could influence energy technology choices in these countries.

Although the U.S. government continues to abstain from setting limits on $CO_2$ emissions, companies are making critical technical decisions that will have enormous impacts on future emissions. In the United States, the high prices of natural gas and the abundance of domestic coal have increased pressure to build more coal-fired power plants. If $CO_2$ reduction regulations are instituted soon, these will encourage the deployment of technologies to capture and store $CO_2$ from those plants. The United States could begin to reduce its global $CO_2$ burden while at the same time becoming a leader in the rapidly emerging market for carbon-abatement technologies.

**Recommended reading**

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