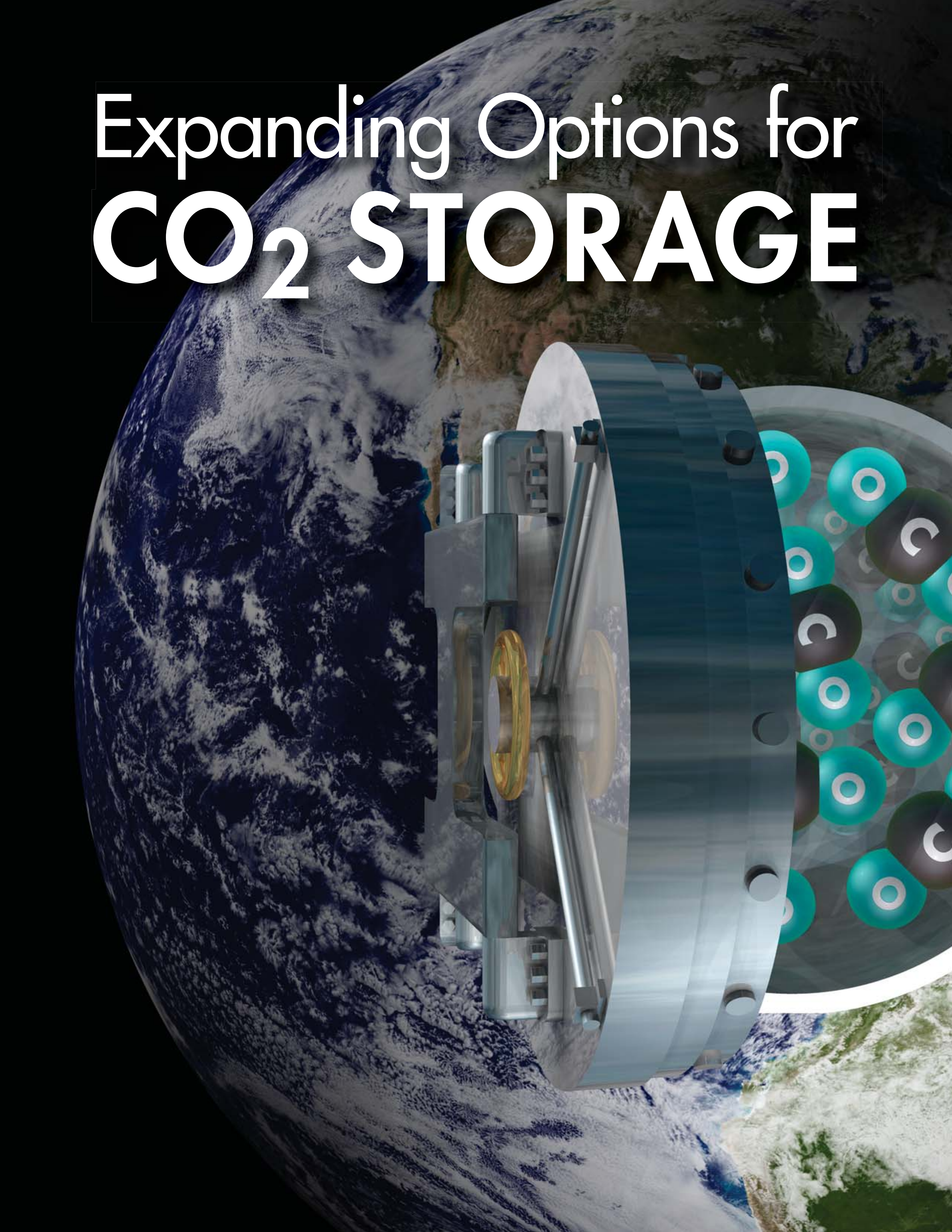
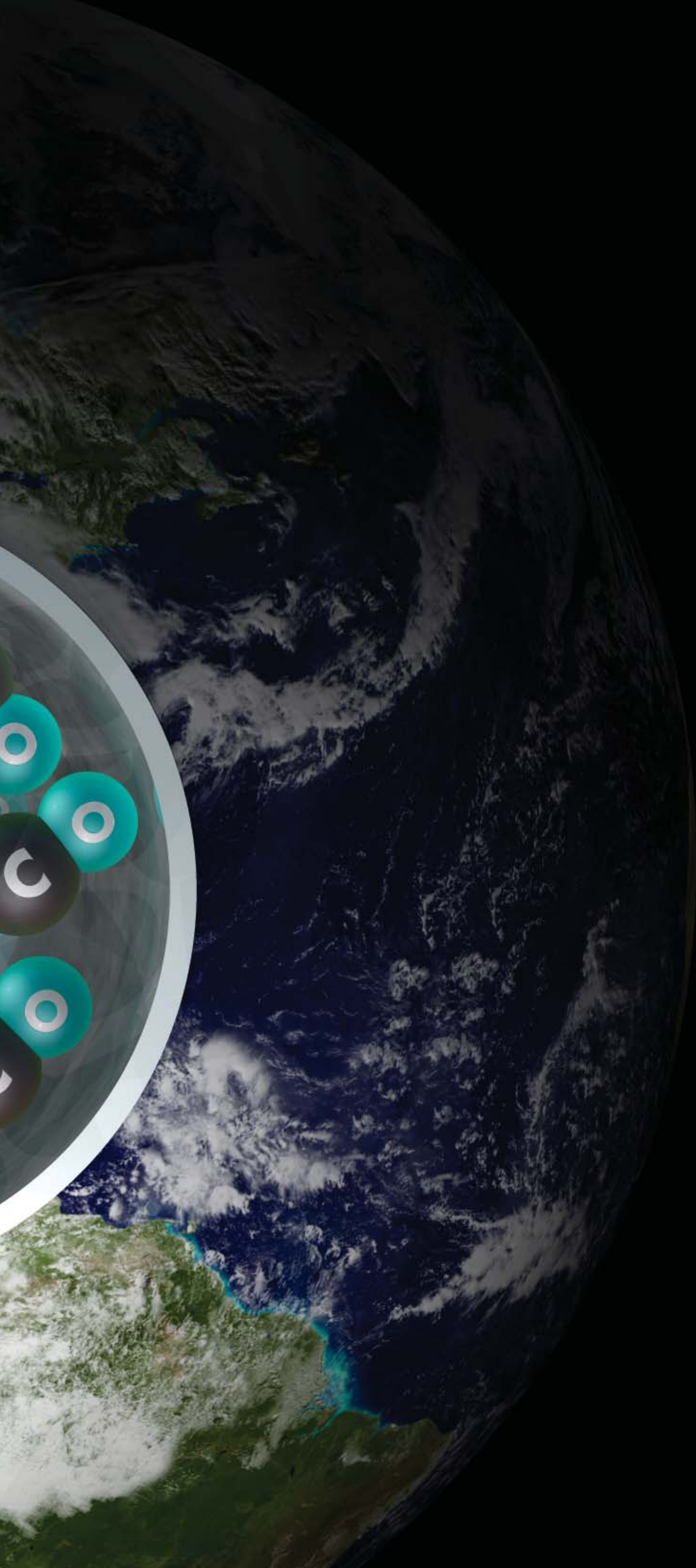
Expanding Options for CO_2 STORAGE





The Story in Brief

While carbon capture gets much of the attention in climate discussions, storage of CO_2 is nonetheless a critical component of the overall climate challenge. Geologic formations potentially suitable for long-term carbon dioxide storage are relatively abundant and widely dispersed in the United States, and technologies for CO_2 transportation and subsurface injection are well established on an industrial scale. But massive expansion of the present infrastructure will be required before enough CO_2 can be stored to make a substantial difference in mitigating atmospheric concentrations. A variety of additional technical and nontechnical concerns also need to be addressed.

ART BY CRAIG DISKOWSKI/EDGE DESIGN. EARTH PHOTO COURTESY VISIBLE EARTH/NASA .

For carbon capture and storage (CCS) to make a major contribution to reducing atmospheric concentrations of greenhouse gases, ways must be found to store CO_2 securely and cost-effectively for centuries or longer. In many ways, the development of storage science and technology is ahead of that for the carbon capture process. Oil companies have been injecting CO_2 into deep geologic formations for more than 30 years to help recover additional petroleum from fields depleted during initial production. Such enhanced oil recovery is currently supported by approximately 3000 miles (4800 km) of dedicated CO_2 pipeline in North America alone, with individual pipes extending for distances up to 500 miles (800 km). In addition, other types of subterranean formations are routinely used for disposal of waste fluids in many parts of the world. Little is known, however, about how suitable various types of underground reservoirs might be for long-term storage of CO_2 and what kinds of risks might be involved. To address these and related issues, a variety of exploratory CCS projects are needed.

The critical challenge will be how to scale up CCS deployment to store huge volumes of CO_2 from the world's power plants and other major facilities—enough to make a significant contribution to stabilizing atmospheric concentrations of this major greenhouse gas. Currently, human activity results in annual carbon dioxide emissions of about 26 gigatons (billion metric tons), or 26 $GtCO_2$. It is expected that modest amounts of capture will be achieved in the first few decades as CCS technology is being developed, but by the end of the century—when international cooperation firmly takes hold and CCS technology is deployed worldwide—the bulk of anthropogenic CO_2 emissions will be captured and stored. Under a hypothetical stabilization policy aimed at keeping atmospheric concentrations below 550 parts per million (ppm), storage of 2 $GtCO_2$/yr will be required around the globe by 2050 and over 22 $GtCO_2$/yr by 2100.

"The United States is fortunate to have an abundance of theoretical CO_2 storage potential, well distributed across most of the country," according to a recent report from the second phase of the Global Energy Technology Strategy Program (GTSP), sponsored by several major research institutions, including EPRI. The report concludes that CO_2 capture and storage sufficient to result in atmospheric stabilization of greenhouse gases "will likely require thousands of CCS-enabled plants deployed over the course of this century, beginning early enough so that gigatons of CO_2 per year are routinely being stored in deep geologic formations around the world by mid-century." The big question is whether sufficient resources can be made available to accomplish this goal.

Storage Basics

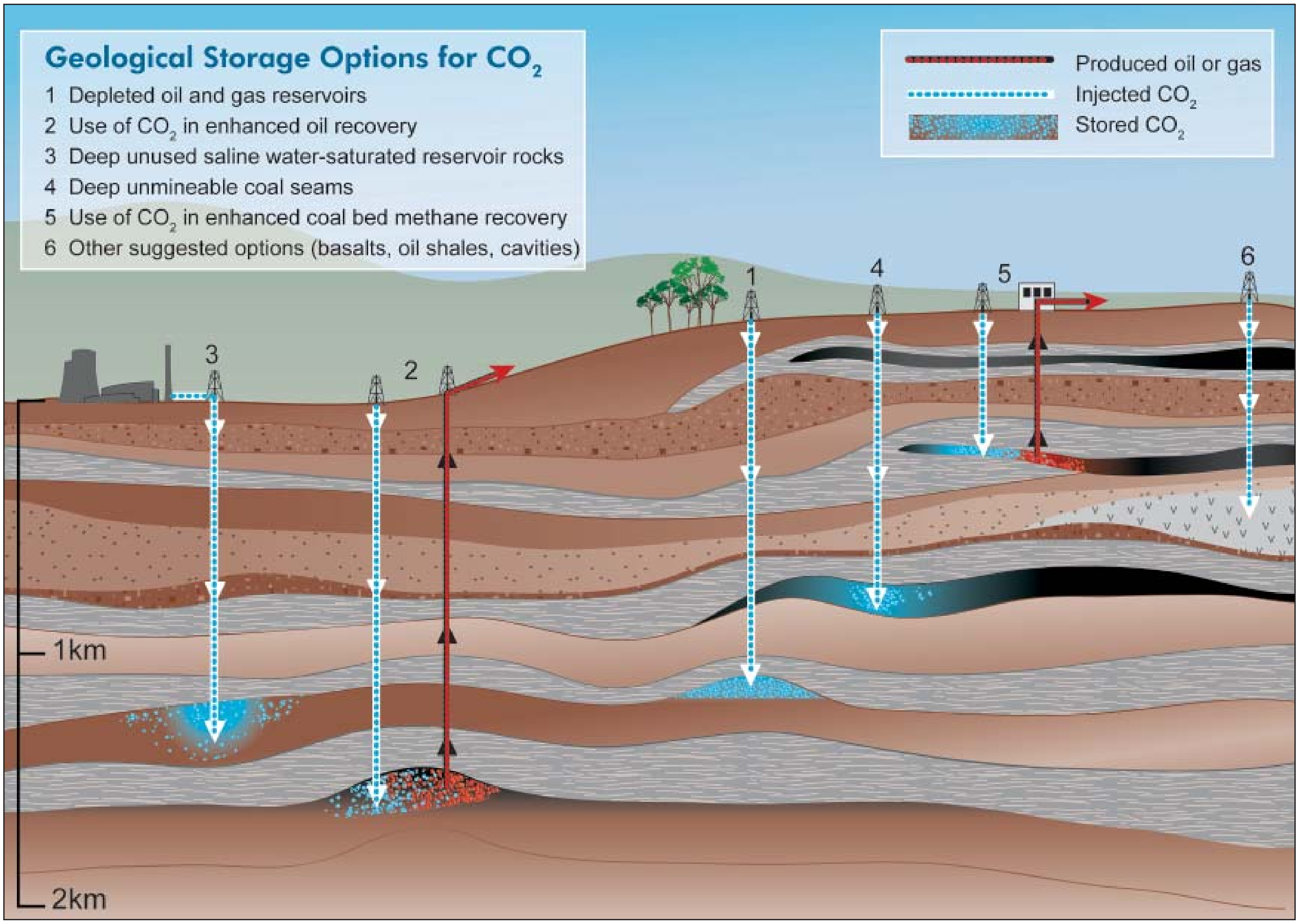
After capture from a power plant, CO_2 would be compressed to a supercritical state in preparation for transport to a suitable storage site. As a supercritical fluid, CO_2 is as dense as a liquid but has gas-like viscosity, making it easier and less costly to transport through dedicated pipelines, which operate in a single, "dense phase" mode at high pressure but ambient temperature. CO_2 can also be further cooled to liquefaction temperature and transported for longer distances by marine tankers in a process similar to that currently used for liquefied natural gas. Each of the individual technologies involved in the transport portion of the CCS process is mature, but integrating and deploying them on a massive scale will be a complex task.

"The question is, how would the necessary pipeline network be established and evolve?" asks EPRI project manager Richard Rhudy. "In particular, early CCS installations will have to create more of their own CO_2 transportation infrastructure than later plants, which will probably have access to a more mature pipeline network."

Initially, the most likely storage sites will be deep geologic formations where porous sediments have been covered by impermeable caprock that can hold the CO_2 in place. In order to maintain the CO_2 in a supercritical state, target reservoir formations will be located at depths greater than about half a mile (0.8 km). By far the most abundant such sites are deep saline formations, where sandstone and carbonate rocks (limestone or dolomite) have numerous voids now partially filled with brine. Injected CO_2 would move into available voids and dissolve in the water, eventually forming stable, solid carbonate compounds with the surrounding material—a process called mineralization.

Depleted oil and natural gas fields, where they are available, also make attractive candidate storage sites. Previously tapped natural gas formations are already often used for gas storage purposes, and the process of injecting CO_2 into such reservoirs would be very similar to the process for storage in deep saline formations. Although CO_2 injection to enhance oil recovery is well established, little is known about how adequately these depleted oil fields might retain CO_2 over a long period, particularly since a significant portion of the currently injected gas re-emerges with the oil produced. An industrial-scale project to clarify the practicality of such storage following enhanced oil recovery is under way in Canada.

Another storage option now being investigated experimentally is to use CO_2 for enhanced methane recovery from unmineable coal seams. In this case, injected CO_2 would chemically bind to the surface of the coal, displacing previously bound methane. One advantage of this approach is that it could take place at shallower depths than those involved in saline formations or depleted oil fields and thus might require less-extensive drilling. Estimates of the potential storage capacity of unmineable coal seams vary widely, however, and the potential of such seams for long-term CO_2 storage remains uncertain. Even less well understood is the possibility of using other types of deep geologic structures, such as porous "interflow" zones in basalt formations, which theoretically might provide an enhanced potential for mineralization.



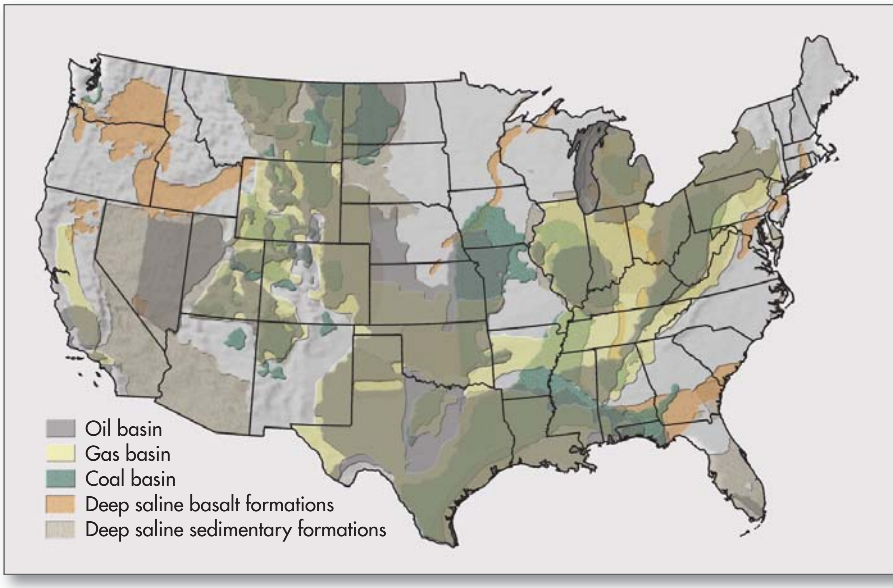
Geologic reservoirs are seen as the best near-term option for the long-term storage of CO_2. Although injection of CO_2 to enhance oil recovery from depleted fields is already a commercially established technique, availability of these fields is likely to be limited. Deep saline formations underlying impermeable caprock will probably provide the largest storage capacity over time, and a number of demonstration projects at such sites are currently under way. Coal seams situated too deep to mine economically present another possibility. (Illustration courtesy Peter Cook, CO2CRC)

Ocean storage has also been suggested, but the idea has aroused objections from the environmental community, and development has not yet progressed to the pilot stage. Nevertheless, the ocean's storage capacity is huge—many times greater than all the currently known geologic sites put together. Because carbon dioxide is soluble in water, natural exchange of CO_2 between the atmosphere and the ocean surface already takes place on a massive scale. Current proposals for ocean storage focus on two possibilities: dissolving the CO_2 in seawater at depths greater than half a mile (0.8 km) or depositing liquefied CO_2 on the sea floor at least 2 miles (3.2 km) down; at this depth, liquid CO_2 is denser than water, so it would form a "lake" on the ocean floor. The potential ecological impacts of such storage options need to be determined, however, before oceans can be used as major CO_2 repositories.

Injection and Leakage

While the concept of geologic storage seems simple enough, a CO_2 injection well is a surprisingly complicated system. Multiple cement casings and provisions for monitoring are required to ensure that the supercritical fluid reaches only appropriate storage formations and stays there. In particular, steps must be taken to keep the CO_2 from interfering with sources of drinking water at shallower depths. In the injection zone itself, special cement must be used to prevent damage to the casing from acids that form when CO_2 reacts with the in situ saline solution. Although the basic technologies for injecting CO_2 safely into deep geologic formations are well established, more-advanced drilling and injection techniques will be needed to optimize storage on the massive scale required. Lateral drilling and injection into multiple, vertically stacked reservoirs, for example, could help make a broader range of potential storage sites accessible.

A variety of measurement, monitoring, and verification (MMV) technologies will also need to be incorporated into a complete storage system to make sure the CO_2



Unlike many other nations, the United States has abundant, well-distributed sites for potential geologic CO_2 storage. Site-specific evaluations will be needed to confirm the sustainability of any particular reservoir.

is not leaking into the surrounding environment. Some off-the-shelf technologies, such as seismic imaging of subterranean formations, are already being used to track the underground migration of injected CO_2, and sampling of groundwater could prove useful for detecting leakage directly. Detecting small rates of leakage over long periods of time, however, will require higher-resolution measurements and the development of highly precise baseline data. More-sensitive MMV techniques that can measure the actual amount of CO_2 in storage may also be needed for purposes of greenhouse gas mitigation reporting.

The issue of leakage is critical from both global and local perspectives. Even gradual leakage from numerous sites may provide enough CO_2 reentering the atmosphere to undermine efforts to stabilize greenhouse gas concentrations. Locally, leakage from an underground storage site could present an immediate hazard to humans and ecosystems. The most dramatic type of CO_2 release would come from a blow-out at an injection well, which could produce high enough concentrations (7–10%) of the gas in the vicinity to endanger human life. Fortunately, this type of release can be detected quickly and stopped using currently available techniques.

Undetected leakage from a faulty well or through ground fractures would probably be more diffuse and primarily affect groundwater and surface ecosystems. In particular, aquifers used as a source of drinking water could be harmed, either by acidification resulting from direct contact with large amounts of CO_2 or by the seepage of brines displaced by CO_2 during the injection process. Because CO_2 is heavier than air, it also could accumulate in low-lying geographic areas or in basements and potentially threaten human health.

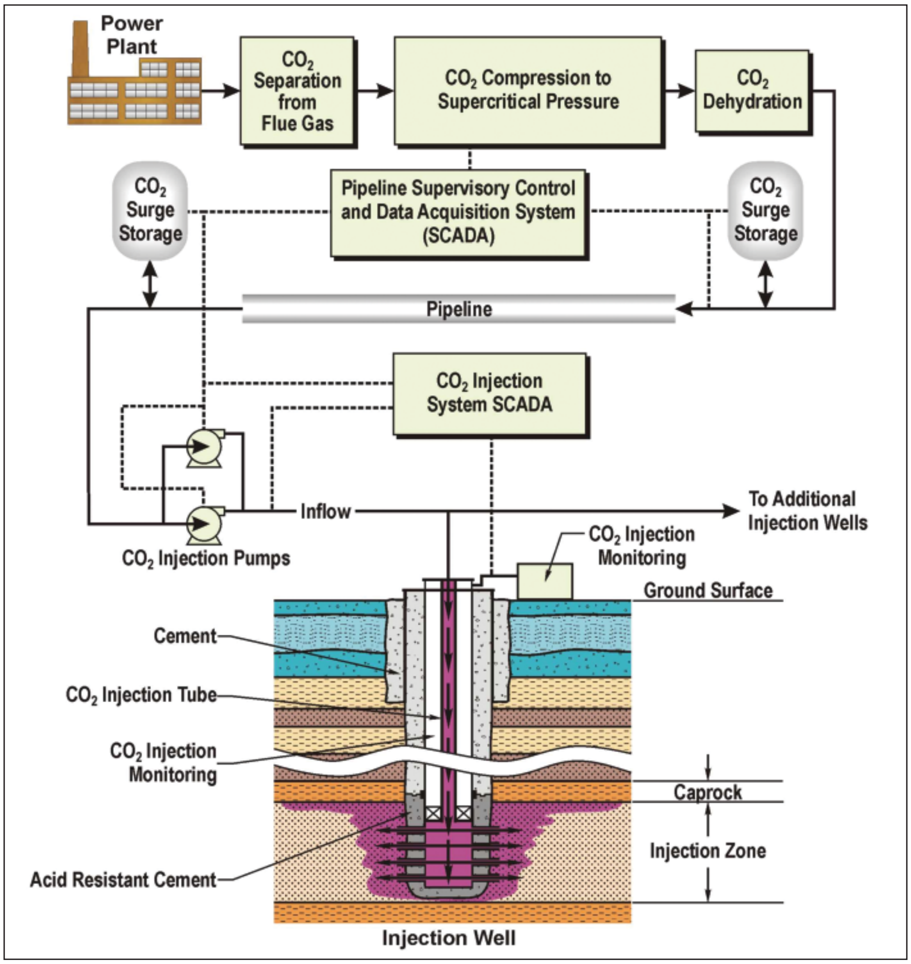
Research is currently under way to improve CO_2 leak detection and develop possible remedial measures. Specifically, MMV technologies are needed that would detect potential leaks long before they pose any danger to water supplies or surface ecosystems. Seismic imaging, for example, can reveal deep subsurface faulting and abandoned wells that might permit leakage by providing a route to the surface, and this type of examination is expected to become a routine part of storage site evaluation. In addition, some experiments are under way to begin to investigate leakage rates for different types of storage and under a variety of injection conditions. Several kinds of remediation techniques also need to be explored, including the extraction and purification of contaminated groundwater, the interception and reinjection of leaking CO_2, and the removal of stored CO_2 for injection elsewhere.

"Careful storage system design and siting, together with methods for early detection of leakage (preferably long before CO_2 reaches the land surface), are ways of reducing hazards associated with diffuse leakage," according to a recent special report by the Intergovernmental Panel on Climate Change (IPCC). "The available monitoring methods are promising, but more experience is needed to establish detection levels and resolution."

Storage Sites and Costs

Like other subterranean resources, potential storage sites for CO_2 are unevenly distributed around the world. Although the United States is particularly fortunate in having abundant, well-distributed sites, other countries may face a real dilemma as they attempt to balance the use of indigenous fossil fuels against the need to curb greenhouse gas emissions in the face of limited CO_2 storage capacity. According to initial GTSP estimates, the world theoretically has more than enough storage capacity—11,000 $GtCO_2$—to meet projected needs for at least a century. Assuming that a variety of carbon management technologies are deployed—including nuclear power, renewable resources, and enhanced end-use efficiency—the demand for CO_2 storage is not expected to exceed 2200 $GtCO_2$ over this century.

Storage adequacy in individual countries, however, varies widely. Japan and Korea, for example, may have their future use of fossil fuels constrained by a lack of onshore geologic CO_2 storage capacity. With their advanced economies, these two countries might potentially be able to meet future limits on greenhouse gases by purchasing emission credits or looking at other options, including offshore geologic storage. However, the case is more problematic for developing countries such as



Future CCS systems will have to integrate CO_2 capture at the power plant with transport, geologic injection, and storage monitoring technologies in a seamless whole on a very large scale. While most of the individual components have been demonstrated in specific applications, experience with integrated end-to-end systems is extremely limited, and large-scale demos for such systems are needed. (Source: Battelle, Joint Global Change Research Institute)

China and India, which depend heavily on readily available coal but have relatively little known CO_2 storage capacity—less than 400 $GtCO_2$ apiece, compared with 3900 $GtCO_2$ in the United States. Little information is available on potential storage sites in these countries, and new surveys of candidate reservoirs will be needed before their capacity is firmly established.

In a carbon-constrained future, storage capacity will, in fact, become an important variable in the global energy/environment equation. "CO_2 storage capacity needs to be seen as a valuable resource," says Tom Wilson, manager of EPRI's Greenhouse Gas Reduction Program. "Regions with abundant storage capacity will be in a better position to continue relying on indigenous fossil fuels and avoid premature retirement of coal-fired power plants."

The largest existing CO_2 point sources are heavily concentrated in a few regions of the world. Those in the United States are responsible for 20% of all global emissions, followed by China, at 18%. The cost of storing the CO_2 from these point sources—dominated by power plants—will be determined by a variety of factors, including availability of suitable geologic formations, distance to a suitable storage site, and competition for the most valuable sites. Developing countries will be particularly challenged to find adequate storage in the midst of rapid economic growth.

Under the most favorable circumstances, CO_2 capture and storage can actually be profitable. An ammonia plant located near a depleted oil field, for example, could sell its CO_2 to a company engaged in enhanced oil recovery. Profit is possible because ammonia plants already produce a fairly pure stream of CO_2, and the major expense involved in the transaction is just the energy used to compress the gas into a supercritical state. By contrast, the net cost of employing CCS at a coal-fired power plant is dominated by the cost of CO_2 capture, which will likely remain greater than any potential profit that could be realized from selling the gas. According to GTSP 2006 estimates, the most favorable situation for a power plant would be a large, coal-fired unit located within 10 miles (16 km) of an opportunity for enhanced coal bed methane recovery—in which case, the net cost would be just over \$20/tCO_2. A more common scenario, in which a coal-fired power plant is located within 25 miles (40 km) of a deep saline formation or within 50 miles (80 km) of a depleted gas field, would involve CCS costs of around \$50/tCO_2.

The specific components that contribute to overall cost estimates for CCS vary widely. The cost of capture and compression can be as low as \$6–\$12/tCO_2 for industrial facilities, such as ammonia or ethanol plants, that already produce a CO_2 stream. In contrast, capture and compression costs for a conventional coal plant using a currently available chemical solvent process would be \$25–\$60/tCO_2, dominated by capital costs and the energy requirements for solvent recycling. For an integrated gasification–combined-cycle (IGCC) power plant using physical absorption, the projected cost is \$25–\$40/tCO_2, dominated by capital expenses. On top of this, long-term transportation and storage costs are expected to stay below approximately \$12–\$15/tCO_2 in the U.S., where access to deep saline formations is readily available. Finally, long-term MMV costs may be as low as a few pennies per ton.

Such cost estimates, however, cannot be considered in isolation by potential CO_2 storage customers in either industrialized or developing economies. The timing of investment presents a particularly difficult dilemma. Should U.S. power producers, for example, just assume they will eventually need access to large storage capacity and preemptively seek out low-cost opportunities, such as those involving enhanced oil and natural gas recovery? Or should they cede these early opportunities to industrial users who could take advantage of them without having to wait for deployment of improved capture technology? Also, from a global perspective, how can the task of establishing a massive new CO_2 transportation and storage infrastructure be initiated and shared most efficiently among various parties to promote the most effective, economical long-term results?

Getting Started

Answers to these questions will ultimately depend on when greenhouse gas restrictions become a fully accepted fact of life for the global electric power industry; nevertheless, some initial efforts need to be started immediately if the necessary technologies and operating experience for CO_2 storage are to be available when needed. A particularly urgent requirement is to gain more experience with integrated, end-to-end CCS systems under realistic conditions. Gaining this experience will take several years' work at utility-scale demonstration projects, some of which are now getting under way in various countries around the world. At the same time, more basic research is needed to develop surveys of candidate CO_2 reservoirs in developing nations like China and India. Such surveys will allow these countries to plan their new generation capacity in a way that will allow future deployment of CCS systems and that may also influence the evolution of their energy infrastructures.

Research is also needed to better understand how CO_2 injection can help improve oil and gas recovery from depleted fields. So far, most analyses have assumed constant incremental recovery improvement, but in fact the response to injection appears to be that production initially increases for

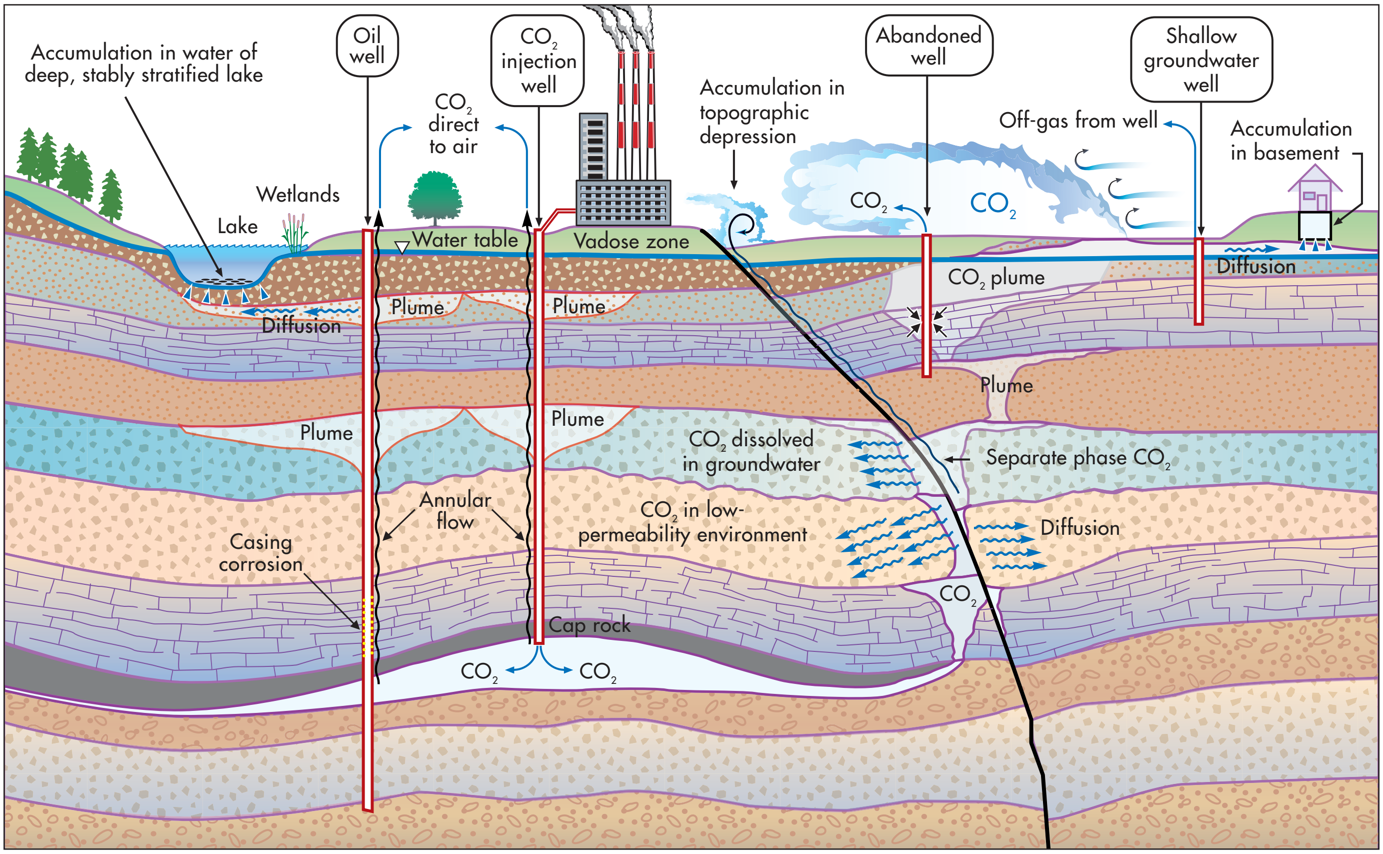
Public-Private Partnerships

For the CCS option to be available in time for large-scale deployment when needed, a series of field tests and integrated technology demonstrations will be required, involving both public and private stakeholders in various geographic regions. To meet this need, the U.S. Department of Energy has launched seven Regional Carbon Sequestration Partnerships, involving state agencies, universities, research organizations, and private companies. (DOE uses the term *sequestration* to include both geologic storage of CO_2 and other efforts to reduce atmospheric concentrations of the gas, such as planting forests.) EPRI is managing specific projects in the West Coast and Southeast regional partnerships (WESTCARB and SECARB, respectively).

The first phase of the partnerships—begun in 2003 and completed in 2005—focused on characterizing regional opportunities for carbon capture and sequestration, and on identifying priorities for field tests. Each of the partnerships developed region-specific data on emissions sources and the potential storage capacity of various geologic formations, and also identified terrestrial ecosystems in the area that might have the capability for enhanced carbon uptake. This information has been incorporated into the National Carbon Sequestration Database (NATCARB) and was also used by the partnerships to calculate the capacity of potential CO_2 storage sites near a specific power plant or other source of emissions and even to estimate the cost of building a pipeline between the source and storage sites. Efforts were also made to identify and address issues related to CCS technology deployment, including safety, public perception, and permitting.

In the second phase of the partnership program, now under way, the task is to conduct 22 geologic injection field tests spread among the partnerships, as well as 13 terrestrial sequestration field tests. The overall goal of these tests is to validate the efficacy of various sequestration technologies in a variety of geologic and terrestrial CO_2 sinks. Specifically, in SECARB, EPRI and Mississippi Power are conducting a pilot project to inject CO_2 into a saline reservoir near Mississippi Power's Plant Daniel; EPRI is managing the pilot with technical support from Southern Company Services (SCS) and cost sharing from SCS, TVA, Mid-American, We Energies, and Ameren. In WESTCARB, the Salt River Project (SRP) and EPRI are conducting an injection test in a saline reservoir in Arizona; EPRI, SRP, and Lawrence Berkeley National Laboratory are managing the project with cost sharing from SRP. These tests will help validate and refine current models for storage in different geologic formations and demonstrate the effectiveness of available monitoring technologies to measure CO_2 movement through a formation. Eventually, the information gathered from the pilot projects will be used to produce guidelines for well construction and operation and to develop strategies for sequestration projects that can be used to optimize the storage capacity of various sink types.

The third, deployment, phase of the program is scheduled to begin in 2008 and continue through 2018. The large-volume storage demonstrations (0.4–4 $MtCO_2$) to be conducted as part of this phase are designed to address long-term issues, such as assessing the ability to sustain high levels of CO_2 injection at a site, improving well design to ensure integrity and increase storage volume, and determining the behavior of geologic formations in response to prolonged injection. The amount of CO_2 stored at individual sites during these demonstrations will approximate the scale needed by commercial facilities.



Properly sited, engineered, and managed geological reservoirs are expected to retain stored CO_2 for hundreds to thousands of years. However, effective monitoring systems will have to consider possible underground CO_2 migration paths through soils and groundwater and likely escape routes, including seismic fissures, abandoned water wells, and the injection wells themselves.

a number of years before peaking and eventually declining. Being able to optimize this process could have a significant impact on the cost of CO_2 storage.

New MMV technologies are also needed that are appropriate for storage systems in many different kinds of geologic formations and under a wide variety of circumstances. Such technologies are likely to provide information about the advantages of pursuing specific types of candidate storage facilities, as well as establishing empirical data on which new regulations and operating procedures can be based.

Finally, the potential for ocean storage of CO_2 may need to be explored more thoroughly, in terms of both risks and costs. One concern is that injection of CO_2 would lead to acidification of seawater—a process already taking place at the ocean surface because of increasing atmospheric concentrations and air-sea exchange of the gas. At present, the effect of increased acidity on marine ecosystems is unknown, and research is urgently needed to improve understanding of the risks involved, with or without injection. The costs of ocean storage also remain highly uncertain, with IPCC estimates ranging over a factor of 5, depending on specific technology and location choices.

"The next decade will be a critical time for developing CCS technologies and gaining experience with operating them," says Tom Wilson. "The vast amount of CO_2 storage ultimately required to make a difference in atmospheric concentrations of greenhouse gases represents a fundamental technological shift. Achieving success in this transition could well determine the long-term viability of coal as a major source of electricity."

In turn, a successful transition will depend on taking a highly proactive approach, adds Richard Rhudy: "What's needed is better-coordinated research into the outstanding questions about storage feasibility and more-systematic development of the massive infrastructure needed."

This article was written by John Douglas. Background information was provided by Tom Wilson (twilson@epri.com) and Richard Rhudy (rrhudy@epri.com).

Further Reading

Carbon Dioxide Capture and Geologic Storage. Technology report from the second phase of the Global Energy Technology Strategy Program (GTSP). 2006. http://www.battelle.org/gtsp.

Carbon Dioxide Capture and Storage. Special report from the Intergovernmental Panel on Climate Change (IPCC). 2006. http://www.ipcc.ch/activity/srccs/index.htm.