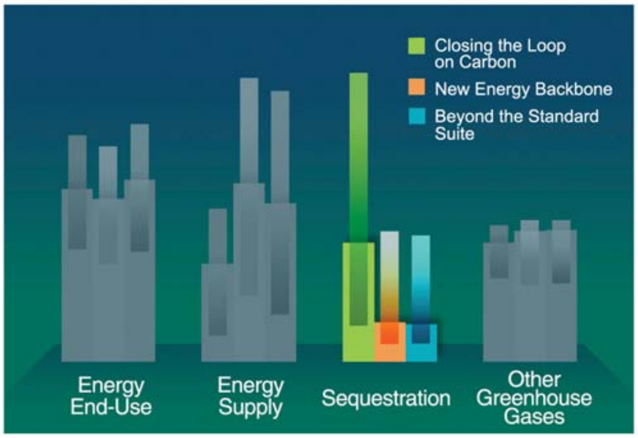
Capturing and Sequestering Carbon Dioxide

Technologies and improved management systems for carbon dioxide (CO_2) capture, storage, and sequestration can potentially reduce CO_2 emissions significantly and help slow the growth in atmospheric CO_2 concentrations. The relative significance of this potential is suggested by Figure 3-19 and highlighted in the figure at right, which draws insights from one set of scenarios analyses that explored various ways to reduce emissions through a suite of these kinds of technologies.

Energy supply technologies incorporating carbon capture and storage were found capable of contributing significantly to future near-zero or very low emissions energy supply. When combined with other sequestration technologies capable of capturing CO_2 from the atmosphere, reduced, avoided, or sequestered global carbon emissions, compared to a reference case, and depending upon assumptions, ranged from low amounts up to nearly 300 gigatons of carbon (GtC) over the course of the 21st century. Although bracketed by a number of uncertainties, this range suggests both the potential role for advanced technology and a long-term goal for contributions from this area in the future global economy.

The three main focus areas for R&D related to carbon cycle management include: (1) the capture of CO_2 emissions from large point sources, such as coal-based power plants, oil refineries, and industrial processes, coupled with storage in geologic formations or other storage media; (2) enhanced carbon uptake and storage by terrestrial biotic systems—terrestrial sequestration; and (3) improved understanding of the potential for ocean storage and sequestration methodologies.[1]

If current world energy production and consumption patterns persist into the foreseeable future, fossil fuels will remain the mainstay of global energy production well into the 21st century. The Energy Information Administration (EIA) projects that by 2025, about 88 percent of global energy demand will be met by fossil fuels, because fossil fuels will likely continue to yield competitive advantages relative to other alternatives (EIA 2004a). In the United States, the use of fossil fuels in the electric power industry accounted for 39 percent of total energy-related CO_2 emissions in 2003, and this share is expected to slightly increase to 41 percent in 2025. In 2025, coal is projected to account for 50 percent of U.S. electricity generation and for an estimated 81 percent of electricity-generated CO_2 emissions. Natural gas is projected to account for 24 percent of electricity generation and about 15 percent of electricity-related CO_2 emissions in 2025 (EIA 2005).



Sequestration
Potential Contributions to Emissions Reduction

Potential contributions of Carbon Capture, Storage, and Sequestration to cumulative GHG emissions reductions to 2100, across arange of uncertainties, for three advanced technology scenarios. See Chapter 3 for details.

Many scenarios of the future suggest that world coal markets will continue to grow steadily over the course of the 21st century, in the absence of CO_2 emissions restrictions. While increased energy efficiency, and use of renewable and nuclear energy afford good

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[1] In this Plan, the three approaches are collectively referred to as "capturing and sequestering carbon dioxide" or "capturing and sequestering carbon."

opportunities for reducing CO_2 emissions, fossil fuel reserves are abundant and economical, making their continued use an attractive option. In various advanced technology scenarios where CO_2 capture and storage technology were assumed to become a cost-competitive technology strategy, fossil-based energy continued to supply a large portion of total electricity consumed into the future (e.g., various studies estimated a 55-70 percent share), even under high carbon management requirements.

Human activities related to land conversion and agricultural practices have also contributed to the buildup of carbon dioxide to the atmosphere. During the past 150 years, land use and land-use changes were responsible for one-third of all human emissions of CO_2 (IPCC 2000). Over the next 100 years, global land-use change and deforestation are likely to account for at least 10 percent of overall human-caused CO_2 emissions. The dominant drivers of current and past land-use-related emissions of CO_2 are the conversion of forest and grassland to crop and pastureland and the depletion of soil carbon through agricultural and other land-management practices (IPCC 2000). Past CO_2 emissions from land-use activities are potentially reversible, and improved land-management practices can actually restore depleted carbon stocks. Therefore, there are potentially large opportunities to increase terrestrial carbon sequestration.

The potential storage and sequestration capacity for CO_2 in various "sinks" is large. Some estimates indicate that about 83 to 131 gigatons of carbon (GtC) could be sequestered in forests and agricultural soils by 2050 (IPCC 2001b), while others estimate geologic storage capacities within a broad range of 300 to 3,200 GtC (IEA 1994a, 1994b, 2000). The ocean represents the largest potential sink for anthropogenic CO_2. Analysis indicates that the ocean is currently absorbing passively some 7.3 Gt of excess atmospheric CO_2 per year (Sabine et al. 2004), partially offsetting the impact on atmospheric concentrations of CO_2 from annual anthropogenic emissions of CO_2 of about 25 Gt per year. The potential storage capacity of the ocean is largely unknown, although some researchers estimate that it might hold thousands of GtC or greater (Herzog 2001, Smith and Sandwell 1997, Hoffert et al. 2002).

There are potential ancillary benefits associated with carbon capture, storage, and sequestration. Many land-management practices that sequester carbon can improve water quality, reduce soil erosion, and benefit wildlife. The injection of CO_2 into geologic structures can be beneficially used to enhance recovery of oil from depleted oil reservoirs and the recovery of methane from unmineable coal seams.

Carbon capture, storage, and sequestration technologies have become a high-priority R&D focus under CCTP because they hold the potential to reduce CO_2 emissions from point sources, as well as from the atmosphere, and to enable continued use of coal and other fossil fuels well into the future. Near-term R&D opportunities include optimizing carbon sequestration and management technologies and practices in terrestrial systems, and accelerating the development of technologies for capturing and geologically storing CO_2 for enhanced oil recovery (EOR). Longer-term R&D opportunities include further development of other types of geologic storage and terrestrial sequestration options, as well as furthering the understanding of both the role oceans might play in storing carbon and the potential consequences of using the oceans for carbon sequestration.

In 2005, the Intergovernmental Panel on Climate Change (IPCC) released its *Special Report on Carbon Dioxide Capture and Storage* (IPCC 2005). While this report is not focused on future R&D options, it serves as an authoritative reference on the state-of-the-art methods in CO_2 capture and storage.

The remaining sections in this chapter summarize the current and potential future research activities and challenges associated with developing carbon sequestration technology. In each section, the description of the current R&D activities includes a hyperlink to the CCTP report, *Technology Options in the Near and Long Term* (CCTP 2005).

6.1 Carbon Capture

Point source CO_2 emissions from power plants vary depending on the combustion fuel, technology, and operational use. Concentrating and capturing CO_2 from flue gas is a technological challenge. Flue gas from conventional coal-fired power plants contains 10 to 12 percent of CO_2 by volume, and flue gas from integrated gasification combined cycle (IGCC) plants contains between 5 and 15 percent CO_2. For a combined cycle gas turbine system, the CO_2 concentration is about 3 percent. The CO_2 in flue gases must be concentrated to greater than 90 percent for most storage, conversion, or reuse applications. Thus, R&D programs are targeted at capture systems that can produce a concentrated and pressurized stream of CO_2 at relatively low cost.

Potential Role of Technology

Large CO_2 point sources, such as power plants, oil refineries, cement plants, and other industrial facilities are considered the most viable sites for CO_2 capture. The current technology for CO_2 capture uses a class of chemical absorbents called amines that remove CO_2 from the gas stream and produce byproduct food-grade CO_2 often used in carbonated soft drinks and other foods. However, the current absorbent process is costly and energy intensive, increasing the cost of a coal-fired plant by 50 to 80 percent (Davison et al. 2001) and energy reductions on the order of 30 percent of the net power generation rate (DOE 1999). Thus, several R&D opportunities are being pursued to reduce CO_2 capture costs and lessen the energy reductions in power generation, or the "net energy penalty."

Technology Strategy

Realizing the possibilities for point source CO_2 capture employs a research portfolio that covers a wide range of technology areas, including post-combustion capture, oxy-fuel combustion, and pre-combustion decarbonization. R&D investments in technologies that use pure oxygen during combustion, pre-combustion de-carbonization technologies, regenerable sorbents, advanced membranes, and hydrate formation can potentially reduce costs, as well as the net energy penalty. After component performance evaluations are completed, the next short-term step would be to conduct pilot scale and slip stream (i.e., diversion of a small stream from the total emissions of an existing plant) level testing of the most promising capture technologies. Larger or full-scale tests might be appropriate within the next few decades to demonstrate and have a suite of capture technologies available for deployment. Fully integrated capture and storage system demonstration (i.e., FutureGen) helps to enable commercial deployment to mitigate the financial and technical performance risks associated with any new technology that must maintain a high availability, such as required by the power generation sector.

Current Portfolio

The metrics and goals for CO_2 capture research are focused on reducing the cost and energy penalty, because analysis shows that CO_2 capture drives the cost of sequestration systems. Similarly, the goals and metrics for carbon storage, measurement, and monitoring are focused on ensuring permanence and safety. All three research areas work toward the overarching program goal of 90 percent CO_2 capture, with 99 percent storage permanence at less than 20 percent increase in the cost of energy services by 2007, and less than 10 percent by 2012. A large-scale demonstration (i.e., FutureGen) would still be necessary.

Across the current Federal portfolio, agency activities are focused on a wide range of technical issues.[2]

- For new construction or re-powering of existing coal-fired power plants, there are pre-combustion decarbonization technology options that provide a pure stream of CO_2 as well as hydrogen at relatively low incremental cost. The most promising option, and the primary focus of current R&D, is **gasification**, in which the hydrocarbon is partially oxidized, causing it to break up into hydrogen (H_2), carbon monoxide (CO), and CO_2, and possibly some methane and other light hydrocarbons. The CO can be reacted with water to form H_2 and CO_2, and the CO_2 and H_2 can be separated. The H_2 used in a combustion turbine or fuel cell, and the CO_2 can be stored.
- New technologies to reduce the capital and energy penalty costs for **post-combustion capture** are also currently under development and include regenerable sorbents, advanced membranes, and novel concepts. One such novel concept, forming CO_2 hydrates to facilitate capture, could be especially attractive for advanced coal conversion systems like the IGCC. A challenge for post-combustion capture is the large amount of gas that must be processed per unit of CO_2 captured. This is especially true for combustion turbines where the concentration of CO_2 in the flue gas can be as low as 3 percent. One area of research is developing gas/liquid contactors where CO_2 gas is chemically absorbed into a liquid, and the resulting mixture is then separated.
- **Oxygen-fired combustion** is also being researched for large CO_2 point sources to determine if CO_2 can be recovered at reasonable cost. In oxygen-fired combustion, oxygen, instead of air, is used in combustion of petroleum coke, coal, or biomass fuels. Oxygen-fired combustion may also be implemented in power systems in which gaseous fuels are combusted with oxygen in the presence of recycled water to produce a steam/CO_2 turbine drive gas. Water is condensed

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[2] See Section 3.1.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-311.pdf.

BOX 6-1

WEYBURN II CO_2 STORAGE PROJECT

DOE is participating in this commercial-scale project that is using CO_2 for EOR. CO_2 is being supplied to the oil field in southern Saskatchewan, Canada, via a 320 kilometer pipeline from a North Dakota coal gasification facility. The goal is to determine the performance and undertake a thorough risk assessment of CO_2 storage in conjunction with its use in EOR. The project will include extensive above and below ground CO_2 monitoring.

from the steam/CO_2 exiting the turbine, leaving sequesterable CO_2. Current R&D investments are focusing on both pulverized coal and circulating fluidized bed designs, and both new plant and retrofit applications. Flue gas can be recycled to control operational characteristics such as thermal flow and flame temperature. Reducing recycle gas in the combustion process results in a higher flame temperature and potentially higher operating efficiency, but this can create other operational challenges. Oxygen is generally supplied via air separation, but "chemical looping" options that extract oxygen from minerals, which are subsequently recirculated and regenerated, are being considered. In addition, there is research underway on low-cost oxygen separation technologies, such as oxygen transport membranes.

- A number of collaborative efforts are currently underway that will contribute to this strategy. **Regional Carbon Sequestration Partnerships** have been organized within the United States, and include networks of state agencies, universities, and private companies focused on determining suitable approaches for capturing and storing CO_2. Four Canadian Provinces are also participating in the effort. The Partnerships are developing a framework to identify, validate, and potentially test the carbon capture and storage technologies best suited for each geographic region and its point sources. During Phase II, beginning in 2005, the Partnerships will pursue technologies for small-scale sequestration validation testing.

- The DOE Carbon Sequestration Program is participating **in collaborations with international partners** in developing new capture and storage technologies. Among these are a cooperative agreement with Canada (Weyburn Project) (Box 6-1) and the Sleipner North Sea Project. The Carbon Sequestration Leadership Forum (CSLF) (Box 6-3) is an international collaborative effort to focus international attention on the development of carbon capture and storage technologies.

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Reduce the costs for sorbents, reducing regeneration energy requirements, and increasing sorbent life.

- Increase understanding of the CO_2 purity requirements to ensure that CO_2 transportation and storage operations are not compromised. In CO_2 transportation, small quantities of SO_2 can lead to two-phase flow and pipeline pressure loss. The presence of water and other minute contaminants might promote acid formation and lead to pipeline and wellbore integrity problems. The history of transporting CO_2 in pipelines that contain substantial amounts of SO_X and NO_X is limited. These components can also impact the integrity of reservoir caprock.

- Develop pre-and post-combustion CO_2 capture technologies that reduce the economic impacts of contaminants in a gas stream. For example, the corrosive nature of some of the contaminants can complicate CO_2 separation processes. Too much nitrogen in the CO_2 can significantly increase the cost of compression prior to geologic storage.

- Develop pre- and post-combustion CO_2 capture technologies that enable storage of criteria pollutants (SO_X, NO_X, H_2S) with the CO_2. In this area, the criteria pollutants are not separated from the CO_2 stream, but rather stored along with the CO_2.

- Continue to improve the cost-effectiveness of CO_2 separation membranes. Performance is improved by more cost-effective designs and materials with increased selectivity to CO_2 (increased CO_2 concentration per single membrane pass), increased throughput (increased flow rate per single membrane pass), and improved chemical stability (a measure of how well the membrane resists chemical reaction with its environment).
- Continue to lower the costs of oxygen used by coal-fueled power plants with separation technologies such as oxygen transport membranes. Success in this area could reduce the costs of oxy-combustion technologies (e.g., circulating fluidized bed designs), as well as gasification technologies.
- Develop an integrated modeling framework for evaluating alternative CO_2 capture technologies for existing and advanced electric power plants.
- Pursue innovative, potentially high-payoff concepts that build on current approaches or that offer entirely new pathways. This would encompass areas such as advanced materials, and chemical and biological processes. Examples include ionization of CO_2, using CO_2 solvents, novel microporous metal organic frameworks (MOFs) suitable for CO_2 separation (Box 6-2), and metabolic engineering to create strains of microbes that feed off CO_2 and produce useful chemical byproducts.
- Continue system integration and advancements of classical MEA-based systems for near-term CO_2 availability.

BOX 6-3

CARBON SEQUESTRATION LEADERSHIP FORUM (CSLF)

Established by the State Department and DOE in February 2003, the CSLF coordinates data gathering, R&D, and joint projects to advance the development and deployment of geologic carbon sequestration technologies worldwide. The CSLF is a particularly attractive mechanism for achieving international cooperation for larger field tests. See http://fossil.energy.gov/programs/sequestration/cslf

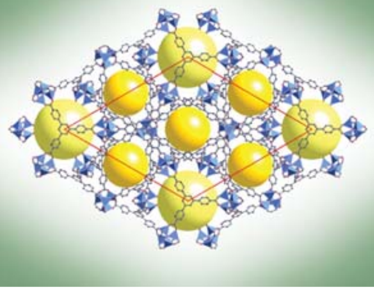
6.2 Geologic Storage

Different types of geologic formations can store CO_2, including depleted oil reservoirs, depleted gas reservoirs, unmineable coal seams, saline formations, shale formations with high organic content, and others. Such formations have provided natural storage for crude oil, natural gas, brine, and CO_2 over millions of years. Each type of formation has its own mechanism for storing CO_2 and a resultant set of research priorities and opportunities. Many power plants and other large point sources of CO_2 emissions are located near geologic formations that are amenable to CO_2 storage. For example, DOE, along with private and public sector partners, is conducting research on the suitability of geologic formations at the Mountaineer Plant in West Virginia.

BOX 6-2

METAL ORGANIC FRAMEWORKS

Scientists have recently developed improved capabilities to synthesize a class of chemical compounds called metal organic frameworks (MOFs), and “tune” their macromolecular properties. Through a project funded by the DOE Sequestration Program, a team of researchers is measuring the CO_2 adsorption isotherms of a set of MOFs to develop a better understanding of what MOF characteristics affect CO_2 adsorption. There have been some early promising results. For example, one particular MOF exhibited a CO_2 sorption capacity that was significantly better than commercially available zeolite sorbents. The increased storage capacity can lower the size and cost of a CO_2 capture system.



MOF 177, Yaghi et. al Nature 427, 523-527 (2004)

Potential Role of Technology

Geologic formations offer an attractive option for carbon storage. The formations are found throughout the United States, and there is extensive knowledge about many of them from the experience of exploration and operation of oil and gas production (Box 6-4). Opportunities exist in the near-term to combine CO_2 storage with EOR and enhanced coal-bed methane (ECBM) recovery using injected CO_2. In 2000, 34 million tons of CO_2, roughly equivalent to annual emissions from 6 million cars, were injected as part of EOR activities in the United States.

Coal-bed methane has been one of the fastest growing sources of domestic natural gas supply. Pilot projects have demonstrated the value of CO_2 ECBM recovery as a way to increase production of this resource.

In the long-term, CO_2 storage in saline and depleted gas formations is being explored. One project is currently in commercial operation, where one million tons of CO_2 per year are being injected in a saline formation at the Sleipner natural gas production field in the North Sea. The Frio Brine Pilot experiment near Houston, Texas, is the first U.S. field test to investigate the ability of saline formations to store greenhouse gases (GHGs). In October 2004, 1,600 tons of CO_2 were injected into a mile-deep well. Extensive methods were used to characterize the formation and monitor the movement of the CO_2. The site is representative of a very large volume of the subsurface from coastal Alabama to Mexico and will provide experience useful in planning CO_2 storage in high-permeability sediments worldwide.

The overall estimated capacity of geologic formations appears to be large enough to store decades to centuries worth of CO_2 emissions, although the CO_2 storage potential of geologic reservoirs depends on many factors that are, as yet, poorly understood. For example, characteristics of reservoir integrity, volume, porosity, permeability, and pressure vary widely even within the same reservoir, making it difficult to establish a reservoir's storage potential with certainty. Assessments of storage capacity could help to better understand the potential of geologic formations for CO_2 storage.

Technology Strategy

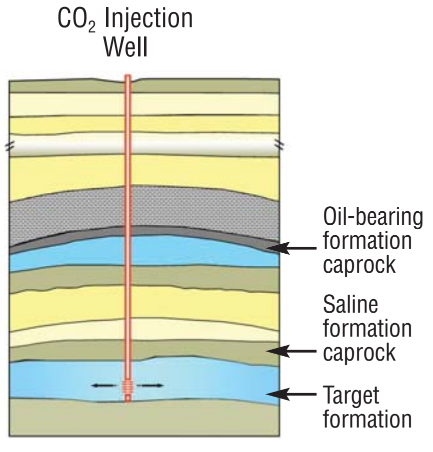
Potential CO_2 sources and sinks vary widely across the United States, and the challenge is to understand the economic, health, safety, and environmental implications of potential large-scale geologic storage projects. The geologic storage program was initiated in 1997 and initially focused on smaller projects. However, field testing is the next step to verify the results of smaller-scale R&D, and the program is taking on larger projects, as knowledge grows and opportunities become available.

In the near-term, activities will focus on addressing important carbon storage-related issues consistent with the Carbon Sequestration Technology Roadmap and Program Plan (DOE 2005). Among these activities are developing an understanding of the behavior of CO_2 when stored in geologic formations. Long-term activities could include understanding and reducing potential health, safety, environmental, and economic risks associated with geologic sequestration.

BOX 6-4

CO_2 STORAGE IN STACKED FORMATION

In a project under the DOE Sequestration program, researchers have pioneered a novel "stacked" approach to CO_2 storage field tests in saline formations. CO_2 is injected into a target formation that underlies a proven oil-bearing seal. The oil-bearing caprock serves as a second barrier against CO_2 migration to the surface and affords scientists an opportunity to learn about the fate and transport of CO_2 injected into a saline formation with negligible risk of adverse environmental consequences.



Courtesy of DOE/NETL

Regional domestic partnerships and international cooperation are viewed as key to deploying carbon storage technologies. Field validation activities test the large-scale viability of point-source capture and storage systems and demonstrate to interested parties the potential of these systems.

Current Portfolio

The goal of geologic storage R&D portfolio is to advance technologies that would enable development of domestic CO_2 underground storage repositories capable of accepting around one billion tons of CO_2 per year. Toward this goal, there is a need to demonstrate that CO_2 storage underground is safe and environmentally acceptable, and an acceptable GHG mitigation approach. Another need is to demonstrate an effective business model for CO_2 EOR and ECBM, where significantly more CO_2 is stored for the long-term than under current practices.

The Federal portfolio for geologic storage activities includes several major thrusts designed to move technologies from early R&D to deployment.[3]

Core RD&D focuses on understanding the behavior of CO_2 when stored in geologic formations. For example, studies are being conducted to determine the extent to which CO_2 moves within the geologic formation, and what physical and chemical changes occur to the formation when CO_2 is injected. This information is needed to ensure that CO_2 storage will not impair the geologic integrity of an underground formation and that CO_2 storage is secure and environmentally acceptable. There are three major research thrusts:

- **Knowledge Base and Technology for CO_2 Storage Reservoirs.** These activities seek to increase the knowledge base and technology options. The petroleum industry has built significant experience over the past few decades on how to inject carbon dioxide into oil reservoirs for EOR. Many of the issues related to injection technologies and gas compression have already been solved. Because oil and gas reservoirs have been able to store gases and other hydrocarbons for geologically significant periods of time (hundreds of thousands to millions of years), they likely have caprocks that will be good seals for CO_2 as well. Furthermore, CO_2 can potentially enhance oil and gas production, which can help mitigate carbon storage costs. However, because the petroleum industry understandably has been focused on resource recovery and not on CO_2 storage, it has not developed procedures to maximize the amount of CO_2 that is stored or to track the CO_2 once it is has been injected to ensure that it remains in the ground. In addition, most well-developed oil fields, by definition, contain many wells that have pierced the caprock for the field, creating potential leakage pathways for CO_2. Research is currently underway to develop technologies to locate abandoned wells, to track the movement of CO_2 in the ground, and to ensure long-term storage, as well as to optimize costs, assess performance, and reduce uncertainties in capacity estimates.

Another attractive option is carbon storage in deep, unmineable coal seams. Not only do these formations have high potential for adsorbing CO_2 on coal surfaces, but the injected CO_2 can displace adsorbed methane, thus producing a valuable byproduct and decreasing the overall storage cost. One potential barrier is the tendency of coal to swell in volume when adsorbing CO_2. This can cause a sharp drop in permeability, thereby impeding the flow of CO_2 and the recovery of methane. Laboratory research, modeling, and field studies are currently being implemented and proposed to gain a better understanding of the processes behind coal swelling and determine if it will be a significant barrier to sequestration in coal seams.

Another option is the use of large saline formations for CO_2 storage, a relatively new concept. About two-thirds of the United States is underlain by deep saline formations that have significant sequestration potential. Since the water in the saline formations is typically not suitable for irrigation or consumption, many opportunities exist for CO_2 to be injected without adverse impacts. The storage capacity of saline formations is enhanced because of the ability of CO_2 to dissolve in the aqueous phase. But, there are uncertainties associated with the heterogeneous reactions that may occur between CO_2, brine, and minerals in the surrounding strata, especially with respect to reaction kinetics. For example, saline formations contain minerals that could react with injected CO_2 to form solid carbonates, which would eliminate potential migration out of the reservoir. On the negative side, the carbonates could plug the formation in the immediate vicinity of the injection well. Researchers are looking into multiphase behavior of CO_2 in saline aquifers and the volume, fate, and

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[3] See Section 3.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-312.pdf.

transport of the stored CO_2. New technologies and techniques are being developed to reduce cost and inefficiency due to leaks and to better define the geology of the saline aquifers. A recent review article addresses the technological challenges of sequestering carbon dioxide in saline formations and coal seams (White et al. 2003).[4]

- **Measurement and Monitoring.** These activities are described more fully in Chapter 8. An important R&D need is to develop a comprehensive monitoring and modeling capability that not only focuses on technical issues, but also can help ensure that geologic storage of CO_2 is safe. Long-term geologic storage issues, such as leakage of CO_2 through old well bores, faults, seals, or diffusion out of the formation, need to be addressed. Many tools exist or are being developed for monitoring geologic storage of CO_2, including well testing and pressure monitoring; tracers and chemical sampling; surface and borehole seismic monitoring; and electromagnetic/geomechanical meters, such as tiltmeters. However, the spatial and temporal resolution of these methods may not be sufficient for performance confirmation and leak detection.
- **Health, Safety, and Environmental Risk Assessment.** Assessing the risks of CO_2 release from geologic storage sites is fundamentally different from assessing risks associated with hazardous materials, for which best practice manuals are often available. In some cases, geologic storage sites may exist near populated areas. Although CO_2 is not toxic or flammable, it can cause suffocation if present at high concentrations. Therefore, the mechanism for potential leaks must be better understood. The assessment of risks includes identifying potential subsurface leakage modes, the likelihood of an actual leak, leak rate over time, and the long-term implications for safe carbon storage. Diagnostic options need to be developed for assessing leakage potential on a quantitative basis.

Two activities cited in Section cited in Section 6.1.3 will continue to play an important role in encouraging the deployment of technologies developed under the core RD&D program. The Regional Partnerships Program[5] is building a nationwide network of Federal, State, and private sector partnerships to determine the most suitable technologies, regulations, and infrastructure for future point source carbon capture, storage, and geologic sequestration in different areas of the country. The Carbon Sequestration Leadership Forum is facilitating the development and worldwide deployment of technologies for separation, capture, transportation, and long-term storage of CO_2.

In addition, the FutureGen project (Box 6-5) is expected to be the world's first coal-fueled prototype power plant that will incorporate geological storage. It will provide a way to demonstrate some of the key technologies developed with Federal support, and demonstrate to the public and regulators the viability of large-scale carbon storage.

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future

BOX 6-5

FUTUREGEN

FutureGen is a public-private initiative to build the world's first integrated carbon capture/storage and hydrogen production power plant. When in operation, the prototype will be the cleanest fossil fuel power plant in the world. An industrial consortium representing the U.S. coal and power industry will work closely with DOE to implement this project. Other countries, including India and South Korea, have recently agreed to participate in the Program. See http://www.netl.doe.gov/coalpower/sequestration/futureGen/main.html.

Courtesy of DOE/NETL

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[4] See Section 3.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-312.pdf.

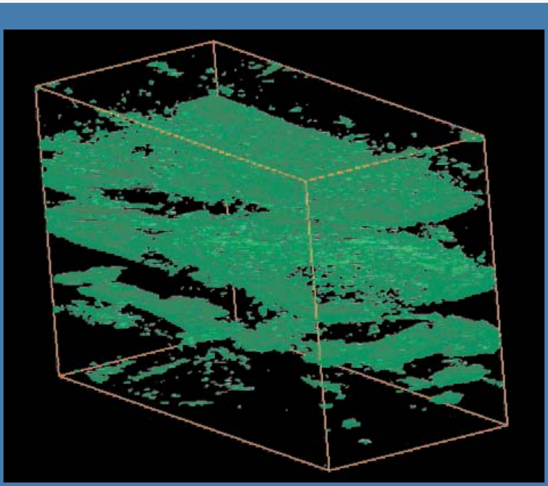
[5] For more information on the Regional Partnerships Program, see http://fossil.energy.gov/programs/sequestration/partnerships.

research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Defining the factors that determine the optimum conditions for sequestration in geological formations, such as depleting oil and gas reservoirs, saline formations, and coal seams, as well as unconventional hydrocarbon bearing formations.
- Developing the ability to predict and optimize CO_2 storage capacity and resource recovery.
- New storage engineering practices that maximize pore volume utilization and accelerate capillary, solubility, and mineral trapping for long-term storage.
- Developing the ability to continuously track the fate and transport of injected CO_2 in different formations. Areas of R&D include geophysical arrays that provide real-time, low-cost, and high-resolution data; and surface and near-surface monitoring techniques such as surface CO_2 flux detectors, injecting tracers in soil gas, and measuring changes in shallow aquifer chemistry for CO_2 leakage.
- Developing models to simulate the migration of CO_2 throughout the subsurface and the effects of injection on the integrity of caprock structures.
- Developing advanced subsurface imaging and alteration of fluid-rock interactions.
- Understanding geochemical reactions (Box 6-6) and harnessing them to enhance containment.
- Developing injection practices that preserve cap integrity, and practices to mitigate leakage to the atmosphere. These practices would include new materials and methods for sealing wells.
- Developing an understanding of CO_2 reactions and movement in shales and other unconventional hydrocarbon-bearing formations that will permit the economic recovery of these hydrocarbons.
- Developing technologies to conduct underground (in-situ) liquefaction and gasification of solid hydrocarbon deposits, such as oil shale and coal.
- Developing cost-effective systems to integrate energy conversion with carbon capture, geologic storage, and subsurface conversion of CO_2 into benign materials or useful byproducts (e.g., through biogeochemical processes that can create methane or carbonates).

BOX 6-6

COAL SWELLING



Computed tomography (CT) scans were taken to image the inside of a block of coal before and after the introduction of high pressure CO_2. Comparison of the two scans showed where CO_2-induced swelling took place in the coal, shown in green. The swelling phenomena is a research challenge, since it can adversely impact the economics of enhanced coal bed methane recovery by reducing the flow of CO_2 into the coal.

Courtesy of DOE/NETL

- Developing improved methods and data for estimating the overall costs of geologic sequestration, including capture, compression, and transportation.
- Improving the understanding of the key elements for effective risk management of geologic storage. Technical objectives are to (1) characterize available storage formations in terms of size and location, (2) characterize leakage rates in order to establish risk management approaches and policies, and (3) conduct large-scale testing on representative formations.
- Reducing the cost of geologic sequestration.
- Improving CO_2 transport systems to provide for public acceptance and regulatory approval, including providing for early leak detection and warning, preventing major pipeline failures, and linking to a national pipeline infrastructure.
- Pursuing breakthrough concepts to reach long-term program goals. Breakthrough concepts are revolutionary and transformational approaches

with potential for low-cost, permanence, and large global capacity. For example, some of the lowest cost estimates for capture/sequestration options are for systems where flue gas components from coal-fueled plants are not scrubbed but rather stored in geologic formations with CO_2. This eliminates the need for costly flue gas cleanup systems, but the potential effects of this option are unknown. Technological innovations could come from concepts associated with areas not normally related to traditional energy R&D fields.

In the long-term, CO_2 capture can be integrated with geologic storage and/or conversion. Many CO_2 conversion reactions are attractive, but too slow for economic chemical processes. Use of impurities in captured CO_2 (e.g., SO_X and NO_X) or additives could possibly enhance geologic storage and provide an opportunity to combine CO_2 emissions reduction with criteria pollutant emissions reduction.

Field tests are the next step to verify R&D results. It is possible that additional tests will eventually be carried out through the Regional Partnerships Program based on analysis of CO_2 sources and sinks by participants to determine the highest benefit projects.

6.3

Terrestrial Sequestration

Terrestrial sequestration can play a significant role in addressing the increase of CO_2 in the atmosphere. A wide range of technologies and practices, including tree planting, forest management, and conservation tillage practices are available to increase the sequestration of carbon in plants and soils. Terrestrial sequestration activities can provide a positive force for improving landscape-level land management and provide significant additional benefits to society, such as improvements in wildlife and fisheries habitat, enhanced soil productivity, reduction in soil erosion, and improved water quality. Terrestrial sequestration represents a set of technically and commercially viable technologies that have the capability to reduce the rate of CO_2 increase in the atmosphere. Given the size and productivity of the U.S. land base, terrestrial sequestration has distinct economic and environmental advantages. Globally, the potential for terrestrial sequestration is also significant, due in part to low-cost opportunities to reduce ongoing emissions from current land-use practices and land conversion and to enhance carbon stocks via afforestation, forest restoration, and improved forest and agricultural management.

Terrestrial sequestration technologies refer broadly to equipment, processes, decision tools, management systems and practices, and techniques that can enhance carbon stocks in soils, biomass, and wood products, while reducing CO_2 concentrations in the atmosphere. Extensions of terrestrial sequestration can use sustainably generated biomass to displace fossil fuels. Examples of terrestrial sequestration technologies include conservation tillage, conservation set-asides, cover crops, buffer strips, biomass energy crops, active forest management, active wildlife habitat management, low-impact harvesting, precision use of advanced information technologies, genetically improved stock, wood products life-cycle management, and advanced bioproducts.

Potential Role of Technology

Increasing terrestrial carbon stocks is attractive because it can potentially offset a major fraction of emissions and serve as a bridge over an interim period, allowing for development of other low-CO_2 or CO_2-free technologies. Carbon stock management technologies and practices that enhance soil and forest carbon sinks need to be maintained once the carbon stock reaches higher levels. Although the benefits can be temporarily reversed by fire, plowing of cropland soils, and other disturbances, the potential improvements in carbon stocks are of such magnitude that they can play a significant overall role in addressing the increase in atmospheric CO_2 emissions from the United States and globally throughout the 21st century.

Other opportunities described in this section can provide benefits essentially indefinitely. For example, changes in crop management practices can reduce annual emissions of trace GHGs; sustainable biomass energy systems can displace fossil fuels and provide indefinite net CO_2 emissions reductions; and enhanced forest management and conversion to durable wood products provide a mechanism to allow forests to continually sequester carbon.

Estimates of the global potential for terrestrial sequestration activities remain uncertain. Such estimates are generally of the technical potential (i.e., the biophysical potential of managed ecosystems to sequester carbon), and disregard market and policy considerations. The IPCC (IPCC 2001c) estimates such technical potential of biological mitigation options (i.e., forest, agricultural, and other land-management activities) to be on the order of 100 GtC cumulative by 2050, at costs ranging from about $0.10 to about $20/t carbon in tropical countries, and from $20/t carbon to $100/t in non-tropical countries. Technical potential estimates for the United States range widely, depending on assumptions about biophysical sequestration rates per hectare, the land area available for different activities, and other factors.

Widely cited estimates of U.S. technical potential for carbon sequestration include about 55–164 teragrams of carbon (TgC) per year for potential sequestration on croplands (Lal et al. 1998); 29–110 TgC per year on grazing lands (Follett et al. 2001); 210 TgC per year on forest land (Joyce and Birdsey 2000); and 91–152 TgC per year on dedicated bioenergy croplands (Tuskan and Walsh 2001). In addition, dedicated bioenergy crops would substitute for fossil fuels, leading to an estimated 450 TgC reduction of CO_2 emissions (Tuskan and Walsh 2001).

These estimates generally represent technical potential that does not reflect barriers to implementation, competition across land uses and sectors, or landowner response to public policies and economic incentives. A recent study of cropland (Eve et al. 2002) indicates a potential of about 66 TgC per year on croplands, toward the lower end of the Lal et al. (1998) range. With regard to bioenergy, a recent DOE/USDA analysis estimates that U.S. forest and agricultural lands could sustainably supply up to 1,300 Tg of biomass/year for bioenergy, similar to the findings of Tuskan and Walsh, but without major shifts in land use or food or fiber production (Perlack et al. 2005). Such a quantity of biomass could displace over 30 percent of current U.S. petroleum consumption.

Technology Strategy

Realizing the opportunities to sequester carbon in terrestrial systems will require managing resources in new ways that integrate crosscutting technologies and practices. A balanced portfolio is needed that supports basic science, technological development, emerging technology demonstrations, innovative partnerships with the private sector, and techniques and metrics for measuring success.

An array of actual and potential technologies can be found in the short-, mid-, and long-terms. In the short-term, some technologies and practices being routinely used can be expanded to increase carbon sequestration. In addition, improvements to many current systems are needed to enable them to enhance above- and below-ground carbon stocks, and manage wood products pools. In the mid to long-term, research can focus on options that take advantage of entirely new technologies and practices.

In the near- and long-term, the R&D portfolio is based on the following:

- Design, develop and demonstrate carbon management strategies consistent with economic and environmental goals for terrestrial ecosystems.
- Improve the understanding of the relationship of carbon management and ecosystem goods and services.
- Determine how terrestrial systems' capacities can be manipulated to enhance carbon sequestration by increasing pool sizes, areal extent, rates of carbon accumulation, and/or longevity of carbon storage in pools.
- Analyze the relationship between natural resource and agricultural policy, and terrestrial sequestration technologies and identifying ways to maximize synergies and avoid potential conflicts between the two.
- Analyze the relationship between energy policy and terrestrial sequestration technologies to enhance understanding of the potential carbon benefits associated with different biofuels.
- Evaluate existing and new market-based adoption and diffusion strategies for terrestrial sequestration technologies.
- Optimize management practices and techniques, informed by analyses of and accounting for all associated GHG emissions and removals, including, to the extent practicable, associated climate-related impacts (such as changes in albedo or surface roughness).
- Improve methods of measuring changes in carbon pools and verifying sequestration rates.
- Develop and analyze incentives for implementation.

Current Portfolio

Much of the research currently underway that could have applications for increasing terrestrial carbon

Terrestrial Sequestration: Woody Crops

Figure 6-1. Growing short rotation woody crops, shown above, provides opportunities to sequester carbon in the soil and biomass feedstocks.

Courtesy of DOE/NREL, Credit: Warren Gretz

sequestration is being undertaken for multiple reasons, often unrelated to climate change. Significant investments are being made in developing sustainable natural resource management systems that provide economic and environmental benefits. In particular, advances have been made in increasing forest productivity, developing effective and environmentally sound uses of crop fertilizers, enhancing soil quality, and in producing biomass feedstocks (Figure 6-1).

Across the current Federal portfolio of terrestrial sequestration-related RD&D, multi-agency activities are focused on a wide range of issues, including the following:

- Cropland management practices can increase the amount of carbon stored in agricultural soils by increasing plant biomass inputs or reducing the rate of loss of soil organic matter to the atmosphere as CO_2. Precision agriculture is a form of site-specific management that can be adapted for improving soil carbon sequestration through a customized carbon sequestering management plan. The goals of this activity are to quantify the carbon sequestration potential of each technology and management practice for various crop production systems, climates, and soils; for various crop production systems, soil types, and geographical areas develop the combinations of practices that optimize soil carbon sequestration, crop production, and profits; develop decision support tools for farmers, other land managers, and policy makers that provide guidance for land-management decisions. For example, create databases that answer questions about how changing from one land-use practice to another will affect carbon sequestration, production, and profits.[6]
- Conversion of marginal croplands to other less-intensive land uses to conservation reserve and buffer areas. The goals of this activity are to quantify the carbon sequestration potential of cropland conservation programs for various climates and soils; develop the combination of practices (e.g., plant species, siting, establishment practices) that optimize carbon sequestration and minimize production losses for various types of cropland conservation practices; and develop decision support tools for farmers, other land managers, and policy makers to inform cropland conservation policies and the relative costs and benefits of different cropland conservation approaches, both in terms of carbon sequestration and production.[7]
- Evaluation of advanced forest and wood products management that may offer significant carbon sequestration opportunities. The goals and milestones of this activity are to increase energy efficiency of forest operations; develop and apply models to better understand the economics of achieving certain GHG mitigation goals through improved forest management; sensors/monitors and information management systems; advanced fertilizers, technologies, and application strategies to improve fertilizer efficiency and reduce nitrogen fertilizer inputs; integrated management strategies and systems to increase nutrient and water use efficiency, increase CO_2 uptake and sequestration and reduce emissions; and wood product management and substitution strategies. The milestones are to have initial systems models and prototype operation on major plantation types in place by 2007 and to deploy first-generation integrated system models and technology by 2010.[8]
- Grazing management to increase amount of carbon in soils. The goals of this activity are to construct quantitative models that describe site-specific interactions among grazing systems, vegetation, soil and climate, and the effects on

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[6] See Section 3.2.1.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3211.pdf.

[7] See Section 3.2.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3212.pdf.

[8] See Section 3.2.1.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3213.pdf.

GHG dynamics; and to develop decision support tools to inform the relative costs and benefits of different grassland management scenarios for carbon sequestration and other conservation benefits.[9]

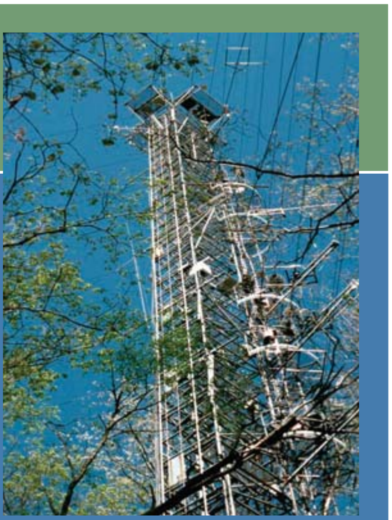
- Restoration of degraded rangelands using low-cost, reliable technologies. The goals of this activity are to develop low-cost, reliable technologies for the restoration of vegetation on degraded arid and semi-arid rangelands; improve decision support for the application of low-cost technologies, such as fire, to control invasive species and to reduce GHG emissions from mesic rangelands; and to develop seed production technology to produce low-cost seeds for reestablishing desired rangeland species. Currently costs are high and seed supply is limited for many cultivars.[10]

- Wetland restoration and management for carbon sequestration and GHG offsets. The goals of this activity are to evaluate various management practices on restored wetlands; delineate and quantify carbon stocks in U.S. wetlands by region and type; develop and demonstrate integrated management strategies for wetland carbon sequestration; and identify wetland areas most likely to be impacted by climate change and prioritize areas for protection.[11]

- Use of biotechnology for modifying the chemical composition of plants and micro-organisms to enhance carbon sequestration (Box 6-7). The goals of this activity are to identify the traits needed in plants and micro-organisms to increase soil carbon sequestration capacity; determine the feasibility of using biotechnology to modify the traits of plants and micro-organisms that can affect soil carbon sequestration; develop systems for monitoring non-target environmental affects associated with plant modifications; develop methods to incorporate genetically modified plant and micro-organisms into cropland and conservation reserve and buffers systems.[12]

BOX 6-7

PHYSIOLOGICAL MECHANISMS OF GROWTH, RESPONSE, AND ADAPTATION IN FOREST TREES



Enhancing the natural capacity of terrestrial ecosystems to store carbon is a viable strategy for stabilizing rising CO_2 concentrations in the atmosphere. However, gains in improving the sequestration potential of croplands, grasslands, and forest lands could be enhanced by major scientific advancements in understanding the processes that control the initial uptake, ultimate chemical forms, and subsequent carbon transfer in plants and soils.

Research carried out by the USDA and DOE is underway to determine the mechanisms that control the quantity and quality of carbon allocated to stems, branches, leaves, and roots of trees as a means of understanding the biological processes that underlie carbon sequestration in trees and soils; understanding controlling genetic mechanisms; and selecting, testing, and demonstrating useful genotypes. Research is focused on several species, including hybrid poplar, willow, and loblolly pine. The studies are designed to determine the interaction of physiological and biogeochemical processes and water and nutrient management on carbon fixation, allocation, storage, and dynamics in forest systems. Field and laboratory studies are being used to quantify and understand carbon dynamics, both above and below ground. Forest researchers hope that these and similar studies will provide the scientific foundation for managing forest systems to enhance carbon sequestration, and improve environmental quality and productivity.

Courtesy of DOE/Office of Science

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[9] See Section 3.2.1.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3214.pdf.

[10] See Section 3.2.1.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3215.pdf.

[11] See Section 3.2.1.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3216.pdf.

[12] See Section 3.2.2.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3221.pdf.

- Development of terrestrial sensors, measurements, and modeling. The goals of this activity are to develop a new generation of sensors, probes, and other instruments to measure soil carbon, GHG flux in situ across a wide variety of agricultural ecosystems.[13]
- Measuring, monitoring, and verification for forests. The goals of this activity are to develop technologies for remote sensing data collection and analysis, in situ instrumentation and monitoring systems, and other measuring and monitoring technologies.[14]
- USDA is providing incentives and supporting voluntary actions by private landowners to reduce GHG emissions and increase carbon sequestration through the portfolio of conservation programs administered by the Department. USDA's actions include financial incentives, technical assistance, demonstrations, pilot programs, education, and capacity building, along with measurements to assess the success of these efforts.

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These iclude:

- Quantifying the carbon sequestration potential for management practices and techniques across all major land uses, including cropland, forests, grasslands, rangelands, and wetlands; across cultivation and management systems; and across regions.
- Designing, developing, and testing management systems to increase carbon sequestration, maintain storage, and minimize net GHG emissions while meeting economic (i.e., forest and agricultural production) and environmental goals. Using a systems approach across sectors and gases will improve the understanding of how technologies are configured to work in a synergistic manner. An example of this approach is in the production of biofuel crops that enhance carbon sequestration, and reduce nitrogen releases to the atmosphere.
- Developing bioenergy and additional durable uses of bio-based products and improve management of residues and wood products.
- Improving biomass supply technologies (harvesting, handling, onsite separation and processing, transportation) to reduce costs and impacts; and enhancing techniques that improve yields, transport, and efficiency of conversion to fuels.
- Exploring the use of trees and other vegetative cover in urban environments to both sequester carbon and reduce the urban heat island effect
- Evaluating terrestrial carbon stock vulnerabilities and stability.
- Improving the understanding of the implications of potential sequestration options on the emissions of other GHGs through comprehensive accounting of all GHG emissions and sinks as land-based carbon sequestration technologies are implemented.
- Improving the performance of technologies and practices to provide additional benefits, including improvements in wildlife habitat; water and air quality; soil characteristics such as stability, water infiltration and retention; and nutrient retention.
- Enhancing sequestration potential through the use of advanced technologies, including bio-based and biotechnology techniques to enhance seed stock qualities, precision water and nutrient application, land management using geographic information system and other tools, and alternative tillage, harvest and fertilizing (e.g., char-based fertilizer) techniques.
- Developing novel alternative technologies such as high-lignin trees for combustion and low-lignin trees to reduce paper processing costs and improved digestibility of fodder and forage.
- Researching biotechnology (genomics, genetics, proteomics), related to biological and ecological processes affecting carbon allocation, storage, and system capacity. Improved understanding of the functional genomics of high-potential biomass crops can increase yields and provide a more effective basis for increasing the conversion efficiency of biomass of fuels, chemicals, and other bioproducts.
- Improving observation and quantification of deforestation, and cost and benefit analysis of options to reduce deforestation.

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[13] See Section 3.2.3.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3231.pdf.

[14] See Section 3.2.3.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3232.pdf.

6.4 Ocean Sequestration

Because of the large CO_2 storage capacity of the ocean, increasing the carbon uptake and storage of carbon in the oceans cannot be ignored (Figure 6-2). Indeed, the ocean is currently playing an important role in consuming significant amounts of anthropogenic CO_2 via passive air-sea exchange, biological uptake, and ocean mixing (e.g., Sabine et al. 2004). This natural rate of CO_2 uptake (about 7.3Gt CO_2/yr), however, is not keeping pace with the rate of current anthropogenic emissions. Also, there are consequences. Ocean acidification that is accompanying the air-sea flux, for example, could have undesirable environmental consequences, if allowed to continue (e.g., Caldeira and Wickett 2003, Feely et al. 2004, Orr et al. 2005).

To understand the additional role the ocean could play in mitigating the effects CO_2 emissions on atmospheric concentrations, several issues must be addressed, including the capacity of the ocean to sequester CO_2, its effectiveness at reducing atmospheric CO_2 concentration levels, the depth and form (e.g., molecular or chemically bound, gas, liquid, or solid) for introduction of the carbon, and the potential for adverse environmental consequences. Ocean storage has not yet been deployed or thoroughly tested, but there have been small-scale field experiments and 25 years of theoretical, laboratory, and modeling studies of intentional ocean storage of CO_2. Nevertheless, there is still much that is unknown and more needs to be learned about the potential environmental consequences to ocean ecosystems and natural biogeochemical cycles.

Although there are a variety of potential ocean carbon sequestration options (see Future Research Directions), two strategies have received the most attention: (1) direct injection of a relatively pure stream of CO_2 into the ocean's deep interior, and (2) iron fertilization to stimulate the growth of nutrient-constrained biota and enhance the ocean's natural biological pump. It is generally thought that direct injection of CO_2 may be technically feasible and effectively isolate CO_2 from the atmosphere for at least several centuries. The primary concerns relate to possible adverse environmental effects. In contrast, the technical feasibility and effectiveness of ocean fertilization remain open to question. Further, whereas direct injection approaches seek to minimize ecosystem impacts, ocean fertilization depends upon the manipulation of ecosystem function over large areas of the ocean's surface.

Figure 6-2. While the oceans play an important role in taking up large amounts of CO_2, there is a need for a better understanding of the potential role of ocean sequestration as a mitigation strategy and its environmental consequences.

Credit: iStockphoto

Over the period of centuries, it is estimated, the oceans will passively take up about 70 percent of global fossil carbon emissions, as CO_2 diffuses into the ocean, is transported across the ocean thermocline, and mixed into deep ocean waters (IPCC 2001a). Direct injection of captured CO_2 would seek to augment to this natural CO_2 flux to the deep sea and, thus, more rapidly slow or reverse the increase in atmospheric CO_2 concentrations. The potential for the ocean to absorb CO_2 over the long-term is large relative to that which would be generated by fossil-fuel resources. But several factors may affect the capacity and desirability of direct injection. Unless consumed by biological or chemical processes, excess CO_2 placed in the deep sea will eventually, via diffusion and ocean circulation, interact with the atmosphere, adding some part of the injected CO_2 to the atmospheric burden. For example, injection of about 8,000 Gt CO_2 to the deep ocean will eventually produce atmospheric CO_2 concentrations of about 750 ppm, even in the absence of additional CO_2 release to the atmosphere. Experiments and models have shown that high concentrations of CO_2 depress ocean pH (i.e., acidification), and thus may harm marine organisms and biogeochemical processes (e.g., Portner et al. 2004, TRS 2005). The true scope and magnitude of such effects could be the subject of further study. Alternatives to direct injection and fertilization have been proposed for CO_2 mitigation strategies. While they may avoid the preceding concerns, they may have environmental, capacity, and cost limitations of their own (see Future Research Directions).

Potential Role of Technology

Ocean sequestration offers the potential to significantly reduce the level of CO_2 concentrations in the atmosphere. There are many technological options envisioned for accomplishing this. Under the direct injection approach, for example, CO_2 could be captured from large point sources, (e.g., fossil-fired power plants, industrial processes, etc.), and then pressurized to liquid form (a supercritical liquid) and injected at depths of 2,000 to 3,000 meters below the surface. Once there, because its density as a liquid is greater than that of sea water, it would be expected to remain for centuries. However, this option has yet to be tested or deployed in a continuous mode at industrial concentrations.

Technology Strategy

The key to any successful technology strategy in this area is to assess adequately (a) the potential of ocean-based options as mitigation strategies; (b) the potential adverse impacts on the ocean biosphere; and the (c) potential effectiveness as evaluated against specific R&D criteria. This includes a research portfolio that seeks to determine, via experimentation and computer simulations, the potential for storing anthropogenic CO_2 in the world's oceans while minimizing negative environmental consequences.

Various studies based on models and ocean observations indicate that the isolation of CO_2 from the atmosphere generally increases with the depth of injection. In the near-term, the key research questions that are related to direct injection involve evaluating the impact of added CO_2 and/or nutrients on marine ecosystems and the biogeochemical cycles to which they contribute. This is being investigated through both observations and modeling of marine organisms and ecosystems, as is now being funded by DOE and the National Science Foundation (NSF), among others. In the long-term, R&D activities could focus on improving an understanding of the effects of elevated concentrations of CO_2 on marine organisms and ecosystems.

Another potential area of study is the effectiveness and environmental and ecological consequences of iron fertilization. Alternative ocean CO_2 mitigation strategies (see "Future Research Directions") pose a different set of environmental and efficacy concerns that need to be evaluated should the effects of direct injection prove to be unacceptable.

Current Portfolio

Ongoing research activities target ocean carbon sequestration using direct injection and iron fertilization. These activities are summarized below:

- **Direct Injection.** Currently, the technology exists for the direct injection of CO_2. Previous laboratory experiments concentrated on establishing an understanding of the processes that occur when CO_2 comes into contact with high pressure seawater. As a result, a much better understanding of the influence of CO_2 hydrates (or clathrates, "solids" in which gas molecules are held in place) on the dissolution processes exists. Additional research conducted by DOE's Oak Ridge National Laboratory simulated a negatively buoyant clathrate. In addition, the Monterey Bay Aquarium Research Institute demonstrated that CO_2 clathrates tend to be negatively buoyant at depths below 3,000 meters. This property of clathrates would presumably reduce the potential ecological impact of CO_2 on the shallow layers of the ocean, where most marine life occurs. It would also increase the length of time that injected CO_2 would remain in the ocean, thus enhancing the effectiveness of CO_2 sequestration by injection. The goal of this R&D activity is to demonstrate that CO_2 direct injection is safe and environmentally acceptable.[15]

Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

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[15] See Section 3.3.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-331.pdf.

- **Direct Injection.** R&D related to direct injection involves improving our understanding of the long-term effects of elevated concentration of CO_2 on marine organisms and ecosystems, as well as mitigation strategies. This could include both in situ and laboratory experiments combined with a program of process modeling aimed at a predictive capability for both biological and physico-chemical parameters.

- **Iron Fertilization.** There are a multitude of R&D opportunities regarding the effectiveness and environmental consequences of ocean fertilization. One question is whether iron enrichment increases the downward transport of carbon from the surface waters to the deep sea. This would help in predicting whether fertilization is an effective carbon sequestration mechanism. Other important questions could be explored: What are the long-term ecological consequences of iron enrichment on surface water community structure, and on mid-water and benthic processes? How can carbon export best be verified?

- **Enhanced Chemical CO_2 Uptake.** The uptake of CO_2 by an aqueous solution can be enhanced by the addition of OH- and/or CO_3- ions. Thus, Kheshgi (1995) pointed out that this could be done on a large scale by adding lime (CaO or CaOH) to the ocean to facilitate its abiotic CO_2 uptake from the atmosphere via the reaction: $Ca(OH)_2 + 2CO_2 \rightarrow Ca^{2+} + 2HCO_3^-$. Importantly, this form of CO_2 mitigation would (1) avoid the need for point-source CO_2 capture, separation, and purification (unlike direct injection, but similar to ocean fertilization); (2) prevent increased ocean acidity because the added CO_2 is neutralized to calcium bicarbonate dissolved in seawater; and (3) permanently store the added carbon in an ionic form that is already abundant in the ocean and not easily degassed back to the atmosphere. The concerns with this approach include the cost and carbon intensity of producing lime from the calcination of limestone, its transport to and dispersal in the ocean, and the environmental consequences of doing so.

- **Enhanced Carbonate Weathering.** CO_2 in power plant flue gases or other industrial gas emissions streams can be brought in contact with calcium carbonate and water, as in weathering processes, and a spontaneous chemical reaction takes place [$CO_2 + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2(HCO_3^-)$]. The resulting dissolved calcium bicarbonate ions can be injected into the ocean (Rau and Caldeira 1999, 2002). This would avoid the need for molecular CO_2 capture and purification and would convert most of the CO_2 to relatively benign, ionic species. Modeling studies showed that such carbon storage would be effective for thousands of years and with less impact to ocean pH than directly injecting a comparable quantity of carbon as molecular CO_2 in the ocean (Caldeira and Rau 2000). Initial cost estimates have shown that for treatment of coastal CO_2 point sources this form of CO_2 mitigation would be less expensive than more conventional molecular CO_2 capture and geologic storage (Sarv and Downs 2002, Rau et al. 2004). However, the true cost, capacity, effectiveness, and environmental impact of this approach need further evaluation.

- **Ocean Burial of Crop Residue.** It has been suggested that organic waste from agriculture be actively buried on the ocean floor, thus enhancing the natural air-to-land-to-ocean carbon sink represented by plant production, soil formation, soil erosion, and river transport to the sea (Metzger and Benford 2001). This approach would prevent some if not most of the oxidation of residue biomass on land and thus eliminate the resulting flux of CO_2 back to the atmosphere. Ocean sites with existing permanent anoxia (e.g. offshore from major river deltas) could be used to slow or avoid oxidation of the biomass once on the ocean floor prior to its permanent burial by natural sedimentation. Concerns to be more thoroughly addressed include (1) the cost of collecting, bundling, transporting, and sinking the residue; (2) the consequences to the fertility of the remaining cropland; and (3) the ultimate impacts to the marine environment.

- **Ocean Disposal of CO_2 Emulsions.** Golomb et al. (2001, 2004) have shown that CO_2 can form a dense emulsion when combined $CaCO_3$ (e.g., limestone) particles under pressure. Such emulsions could be formed prior to or during ocean CO_2 injection, with the resulting CO_2-rich mass sinking to and stored on the ocean floor. Studies suggest that at deep ocean temperatures and pressures, the CO_2 might be sequestered indefinitely by this approach. The method and cost of (1) initial CO_2 capture and purification, (2) limestone/carbonate preparation, and (3) transporting reactants to ocean sites, as well as the marine environmental consequences of this approach are among the issues that remain to be addressed in detail.

- **Other Methods.** The preceding list of CO_2 mitigation options involving the ocean may not be exhaustive, and any future research portfolio should be open to the possibility of new approaches or mix of approaches.

In summary, the ocean is currently playing an important role in mitigating significant amounts of anthropogenic CO_2 via passive air-to-sea transfer. The chemical impacts accompanying this flux, including ocean acidification, may have serious environmental consequences. Any scheme that introduces additional molecular CO_2 (unreacted or uncombined) to the ocean will contribute to these impacts. There are alternative, potentially promising ways for ocean carbon addition that lessen or avoid these impacts. However, such approaches are likely to be attended by other unresolved issues of their own, and the economic and environmental costs and benefits of such schemes could be the subject of further research. All options for safely using the ocean's potential for carbon uptake need to be seriously and carefully considered.

6.5 Summary

The development of the technical, economic, and environmental feasibility and acceptability of CO_2 sequestration strategies has important implications for meeting the needs for food, fiber, and energy while minimizing GHG emissions. As the current energy infrastructure evolves around fossil fuels, the viability of sequestration could provide many options for a future of near-net-zero GHG emissions. Carbon sequestration has the potential to reduce the cost of stabilizing GHG concentrations in the atmosphere, conceivably at lower costs than other alternatives, if successful, and further support domestic and global economic growth. If carbon sequestration were to prove technically and economically viable, fossil fuels could continue to play an important role as a primary energy supply.

This chapter reviews various forms of advanced technology, their potential for reducing emissions by capturing, storing, and sequestering carbon dioxide, and the R&D strategies intended to accelerate the development of these technologies. Although uncertainties exist about both the level at which GHG concentrations might need to be stabilized and the nature of the technologies that may come to the fore, the long-term potential of advanced technologies to capture, store, and sequester carbon dioxide is estimated to be significant, both in reducing emissions (as shown in the figure at the beginning of this chapter) and in reducing the costs for achieving those reductions, as suggested by Figure 3-14. Further, the advances in technology development needed to realize this potential, as modeled in the associated analyses, animate the R&D goals for each carbon dioxide capture and sequestration technology area.

As one illustration among the many hypothetical cases analyzed,[16] GHG emissions were constrained to a high level over the course of the 21st century in such a way that a stabilized GHG concentration levels could ultimately be attained. The lowest-cost arrays of advanced technology in capturing, storing, and sequestering carbon dioxide, when compared to a reference case, resulted in reduced or avoided emissions of between 10 and 110 GtC over 100 years. The breadth of this range is due to a large degree of uncertainty at this point in time in the cost and viability of some sequestration technologies. For perspective, these quantities amounted to, roughly, between 2 and 20 percent of all GHG emissions reduced, avoided, captured and stored, or otherwise withdrawn and sequestered needed to attain this level over the same period. Similarly, the costs for achieving such emissions reductions, when compared to the reference case, were reduced by roughly a factor of 3. See Chapter 3 for other cases and other scenarios.

As described in this chapter, CCTP's technology development strategy supports achievements in this range. The overall strategy is summarized schematically in Figure 6-3. Advanced technologies are seen entering the marketplace in the near-, mid-, and long-terms, where the long-term is sustained indefinitely. Such a progression, if successfully realized worldwide, would be consistent with attaining the potential for carbon dioxide capture and sequestration portrayed at the beginning of this chapter.

The timing and pace of technology adoption are uncertain and must be guided by science and supported by appropriate policies (see Approach 7, Chapters 2 and 10). In the case of the illustration above, the first GtC per year (1GtC/year) of reduced

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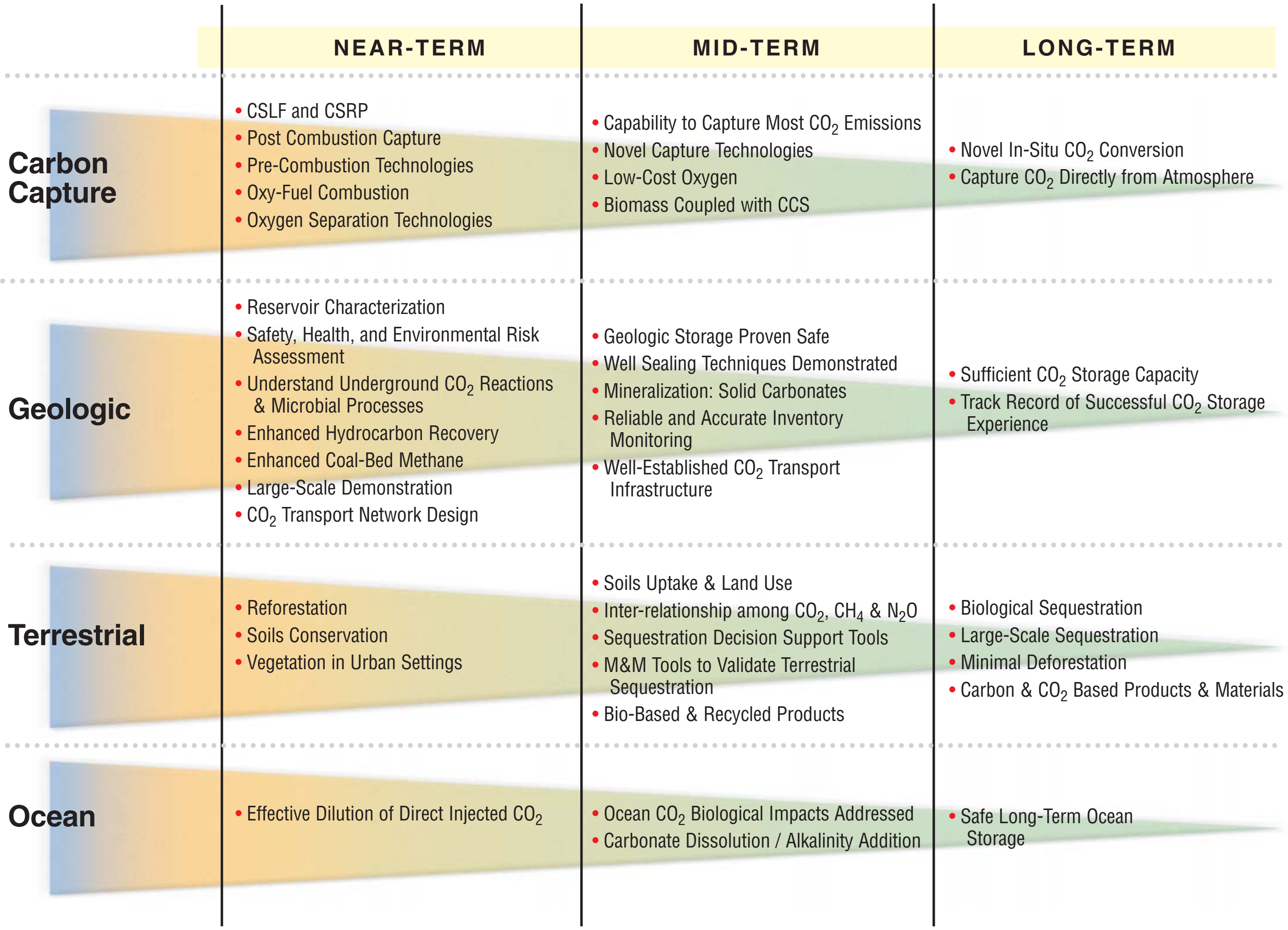
[16] In Chapter 3, various advanced technology scenarios were analyzed for cases where global emissions of GHGs were hypothetically constrained. Over the course of the 21st century, growth in emissions was assumed to slow, then stop, and eventually reverse in order to ultimately stabilize GHG concentrations in the Earth's atmosphere at levels ranging from 450 to 750 ppm. In each case, technologies competed within the emissions-constrained market, and the results were compared in terms of energy (or other metric), emissions, and costs.

or avoided emissions, as compared to an unconstrained reference case, would need to be in place and operating, roughly, as early as 2040. For this to happen, a number of new or advanced technologies to capture, store, and sequester carbon dioxide would need to penetrate the market at significant scale before this date. Other cases would suggest faster or slower rates of deployment. See Chapter 3 for other cases and other scenarios.

Throughout Chapter 6, the discussions of the current activities in each area support the main components of this approach to technology development. The activities outlined in the current portfolio sections address the highest-priority investment opportunities for this point in time. Beyond these activities, the chapter identifies promising directions for future research, identified in part by the technical working group and assessments and inputs from non-Federal experts. CCTP remains open to a full array of promising technology options as current work is completed and changes in the overall portfolio are considered.

Technologies for Goal #3: CO_2 Capture, Storage, and Sequestration



	NEAR-TERM	MID-TERM	LONG-TERM
Carbon Capture	• CSLF and CSRP • Post Combustion Capture • Pre-Combustion Technologies • Oxy-Fuel Combustion • Oxygen Separation Technologies	• Capability to Capture Most CO_2 Emissions • Novel Capture Technologies • Low-Cost Oxygen • Biomass Coupled with CCS	• Novel In-Situ CO_2 Conversion • Capture CO_2 Directly from Atmosphere
Geologic	• Reservoir Characterization • Safety, Health, and Environmental Risk Assessment • Understand Underground CO_2 Reactions & Microbial Processes • Enhanced Hydrocarbon Recovery • Enhanced Coal-Bed Methane • Large-Scale Demonstration • CO_2 Transport Network Design	• Geologic Storage Proven Safe • Well Sealing Techniques Demonstrated • Mineralization: Solid Carbonates • Reliable and Accurate Inventory Monitoring • Well-Established CO_2 Transport Infrastructure	• Sufficient CO_2 Storage Capacity • Track Record of Successful CO_2 Storage Experience
Terrestrial	• Reforestation • Soils Conservation • Vegetation in Urban Settings	• Soils Uptake & Land Use • Inter-relationship among CO_2, CH_4 & N_2O • Sequestration Decision Support Tools • M&M Tools to Validate Terrestrial Sequestration • Bio-Based & Recycled Products	• Biological Sequestration • Large-Scale Sequestration • Minimal Deforestation • Carbon & CO_2 Based Products & Materials
Ocean	• Effective Dilution of Direct Injected CO_2	• Ocean CO_2 Biological Impacts Addressed • Carbonate Dissolution / Alkalinity Addition	• Safe Long-Term Ocean Storage

Figure 6-3. Technologies for Goal #3: CO_2 Capture, Storage, and Sequestration
(Note: Technologies shown are representations of larger suites. With some overlap, "near-term" envisions significant technology adoption by 10–20 years from present, "mid-term" in a following period of 20–40 years, and "long-term" in a following period of 40–60 years. See also List of Acronyms and Abbreviations.)

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