Introduction

Fossil fuels will remain the mainstay of world energy production well into the 21st century. Coal, for example, is abundant, comparatively inexpensive, and geographically diverse. The International Energy Agency estimates that overall world coal use will increase by about 50 percent between now and 2030, and by nearly 67 percent for power generation, mostly in developing countries.

The United States has an estimated 250-year supply of coal. In terms of energy value (Btus), coal constitutes approximately 95 percent of U.S. fossil energy reserves. Because of its abundance and low cost, coal now accounts for more than half of the electricity generated in the United States.

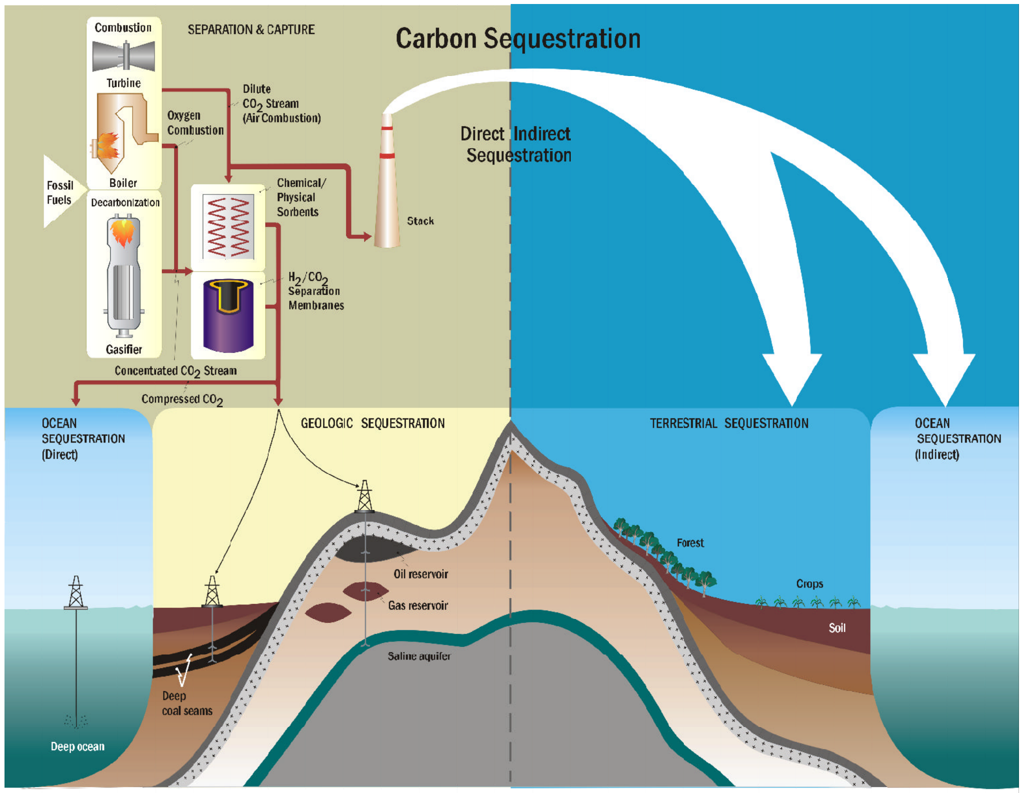
Availability of fossil fuels to provide clean, affordable energy is essential for the prosperity and security of the United States. However, increased concentrations of carbon dioxide (CO_2) due to increased carbon emissions are expected. To stabilize and ultimately reduce concentrations of this greenhouse gas, it will be necessary to employ new technologies, such as carbon sequestration, to capture carbon dioxide and other greenhouse gas emissions before they are released into the atmosphere.

> ***"...our investment in advanced energy and sequestration technologies will provide the breakthroughs we need to dramatically reduce our [greenhouse gas] emissions in the longer term."***
>
> **President George W. Bush**
> **Global Climate Change Policy Book**
> **February 2002**

Along with improved efficiency and low carbon fuels, carbon sequestration is a third option for greenhouse gas mitigation. Carbon sequestration is the process of capturing CO_2 emissions, which would otherwise be released into the atmosphere, and permanently storing them in geologic formations, including oil and gas reservoirs, unmineable coal seams and deep saline reservoirs, or deep in the oceans. Carbon sequestration can also be done terrestrially in forests, crop and agricultural lands, and in wetlands. Additionally, naturally occurring reservoirs of CO_2 can be found in geologic formations throughout the United States and the world.

The Global Climate Change Initiative set forth by President George W. Bush calls for an 18 percent reduction in the carbon intensity of the United States economy by 2012. Technology solutions that provide energy-based goods and services with reduced greenhouse gas emissions are the President's preferred approach to achieving the Global Climate Change Initiative goal.

Recognizing the importance of carbon sequestration, the U.S. Department of Energy (DOE) established a Carbon Sequestration Program within the Office of Fossil Energy (FE) in 1997, and a basic research program in the Office of Science (OS) in 1999. Both programs seek to move sequestration technology forward so that its potential can be realized. They also directly implement the President's Global Climate Change Initiative, as well as several National Energy Policy goals targeting the development of new technologies, market mechanisms, and international collaboration to reduce greenhouse gas intensity and greenhouse gas emissions.



There are two main types of sequestration: direct sequestration, where CO_2 is removed from energy systems (such as power plants and oil refineries) and is permanently stored or converted to value-added products, and indirect sequestration, where CO_2 is removed from the atmosphere by enhanced natural processes.

To be successful, the techniques and practices to sequester carbon must meet the following requirements:

- be effective and cost-competitive,
- provide stable, long-term storage, and
- be environmentally benign.

Using present technology, estimates of sequestration costs are in the range of $100 to $300/ton of carbon emissions avoided. The overarching goal of sequestration research and development is to achieve sequestration with less than a ten percent increase in energy system costs, or roughly $10/tonne CO_2 avoided. Achieving this goal would save the United States trillions of dollars.

Near term research is examining and identifying a spectrum of science-based sequestration approaches that have the greatest potential to yield the cost-effective technologies that are required. In the mid-term, sequestration pilot testing will develop options for direct and indirect sequestration, and the measuring, monitoring, and verification technologies and techniques necessary to quantify actual CO_2 storage. In the long term, the technology products will be more revolutionary and rely less on site-specific or application-specific factors to ensure economic viability.

The sequestration portfolio covers the entire carbon sequestration "life cycle" of capture, separation, transportation, and storage or reuse, as well as the capability to measure and monitor the amount of CO_2 stored. Specifically, the DOE's carbon sequestration research can be broken down into six major research elements:

- Cost-effective CO_2 capture and separation processes. (FE)
- CO_2 sequestration in geological formations including oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs. (FE, OS)
- Direct injection of CO_2 into the deep ocean and stimulation of phytoplankton growth. (FE, OS)
- Improved full life-cycle carbon uptake of terrestrial ecosystems. (FE, OS)
- Breakthrough chemical, biological, and decarbonization concepts. (FE, OS)
- Measurement, monitoring and verification of stored CO_2. (FE, OS)

Current carbon sequestration research within FE consists of more than 60 highly leveraged projects with more than 40 percent of the funding provided by industry and international partners, such as BP, American Electric Power, Chevron/Texaco, and the Department of Natural Resources of Canada.

In November, 2002, DOE Secretary Spencer Abraham announced that the FE sequestration program intends to create a nationwide network of up to ten "regional sequestration partnerships" beginning in September, 2003. The partnerships will help determine the sequestration technologies, regulations, and infrastructure that are best suited for specific regions of the country.

Carbon Separation and Capture

Carbon dioxide separation and capture is the first step of direct sequestration and entails capturing CO_2 from power plants, industrial processes, fuels manufacturing, and other energy systems before it is emitted to the atmosphere.

This technology exists today, but it can raise energy costs by 50 percent or more. Driving the need for separation and capture technology is the fact that one-third of U.S. man-made CO_2 emissions come from power plants. The challenge is that these emissions are dispersed and not concentrated enough to be captured cost-effectively. The Carbon Sequestration program is pursuing evolutionary improvements in existing CO_2 capture systems, and exploring revolutionary new capture and sequestration concepts to achieve more concentrated CO_2 streams.

Separating and capturing CO_2 from energy systems can be accomplished before, during, or after a high-carbon fuel is combusted. Pre-combustion decarbonization research aims to remove CO_2 in concentrated streams before a fuel is burned. Oxygen-fired combustion research focuses on using oxygen (rather than air) to either gasify or combust high-carbon fuels, resulting in a more concentrated stream of CO_2 that can be captured within the system. Post-combustion research and development centers on techniques to remove CO_2 from flue gas exhaust.

DOE's Carbon Sequestration Programs fund separation and capture R&D projects covering a wide range of technology areas including: amine absorbents, carbon adsorbents, membranes, sodium and other metal-based sorbents, electrochemical pump, hydrates, and mineral carbonation. Also, advanced fuel conversion technologies such as gasification, oxygen combustion, and advanced steam reforming are being evaluated for their impact in reducing overall carbon emissions in fossil-fuel energy systems.

Opportunities for significant cost reductions exist since very little R&D has been devoted to CO_2 capture and separation technologies. Several innovative schemes have been proposed that could significantly reduce CO_2 capture costs, compared to conventional processes. For example, "one box" concepts that combine CO_2 capture with sulfur dioxide, nitrogen oxides, and mercury control can lessen or eliminate the need for scrubbers and other emissions abatement systems. This type of systems integration technology is being explored through laboratory- and pilot-scale experiments, and ultimately, may be used in the Energy Department's commercial FutureGen facility.

Geologic Sequestration

Geologic sequestration is a form of direct sequestration where CO_2 is stored in underground formations, such as depleted oil and gas reservoirs, unmineable coal seams, and saline reservoirs. These formations have the capacity, structure, seals, porosity, and other properties that make them amenable to decades or centuries worth of CO_2 storage.

Oil and Gas Reservoirs. In some cases, production from an oil or natural gas reservoir can be enhanced by pumping CO_2 gas into the reservoir to push out the product, which is called enhanced oil or gas recovery. The United States is the world leader in enhanced oil recovery technology, using about 32 million tons of CO_2 per year for this purpose. From the perspective of the sequestration programs, enhanced oil recovery represents an opportunity to sequester carbon at low net cost due to the revenues from recovered oil or gas.

In an enhanced oil recovery application, the integrity of the CO_2 that remains in the reservoir is well-understood and very high, as long as the original pressure of the reservoir is not exceeded. The scope of this enhanced oil recovery application is currently economically limited to point sources of CO_2 emissions that are near an oil or natural gas reservoir.

Unmineable Coal Seams. Coal beds typically contain large amounts of methane-rich gas that is adsorbed onto the surface of the coal. The current practice for recovering coal bed methane is to depressurize the bed, usually by pumping water out of the reservoir. An alternative approach is to inject CO_2 gas into the bed. Tests have shown that CO_2 is roughly twice as adsorbing on coal as methane, giving it the potential to efficiently displace methane and remain sequestered in the bed. CO_2 recovery of coal bed methane has been demonstrated in limited field tests, but much more work is necessary to understand and optimize the process.

Similar to the by-product value gained from enhanced oil recovery, the recovered methane provides a value-added revenue stream to the carbon sequestration process, creating a low net cost option. The United States' coal resources are estimated at 6 trillion tons, and 90 percent of it is unmineable due to seam thickness, depth, and structural integrity.

Another promising aspect of CO_2 sequestration in coal beds is that many of the large unmineable coal seams are near electricity generating facilities that are large point sources of CO_2 gas. Thus, limited pipeline transport of CO_2 gas would be required. Integration of coal bed methane with a coal-fired electricity generating system can provide an option for additional power generation with low emissions.

Saline Formations. Sequestration of CO_2 in deep saline formations does not produce value-added by-products, but it has other advantages. First, the estimated carbon storage capacity of saline formations in the United States is large, making them a viable long-term solution. It has been estimated that deep saline formations in the United States could potentially store up to 500 billion tonnes of CO_2. Second, most existing large CO_2 point sources are within easy access to a saline formation injection point. Therefore, sequestration in saline formations is compatible with a strategy of transforming large portions of the existing U.S. energy and industrial assets to near-zero carbon emissions via carbon sequestration.

Assuring the environmental acceptability and safety of CO_2 storage in saline formations is important. Determining that CO_2 will not escape from formations and either migrate up to the earth's surface or potentially contaminate drinking water supplies is a key aspect of this research.

Although much work is needed to better understand and characterize sequestration of CO_2 in deep saline formations, a significant baseline of information and experience exists. For example, as part of enhanced oil recovery operations, the oil industry routinely injects brines from the recovered oil into saline reservoirs, and the U.S. Environmental Protection Agency (EPA) has permitted some hazardous waste disposal sites that inject liquid wastes into deep saline formations.

Since 1996, the Norwegian oil company, Statoil, has injected approximately one million tonnes per year of recovered CO_2 into the Utsira Sand, a saline formation under the North Sea associated with the Sleipner West Heimdel gas reservoir. The amount being sequestered is equivalent to the output of a 150-megawatt coal-fired power plant. This is the only commercial CO_2 geological sequestration facility injecting CO_2 into a saline formation.

Terrestrial Sequestration

Terrestrial sequestration is a form of indirect sequestration whereby ecosystems (*e.g.*, forest and agricultural lands, and wetlands) are maintained, enhanced, or manipulated to increase their ability to store carbon beyond current conditions.

Enhancing the natural processes that remove CO_2 from the atmosphere is thought to be one of the most cost-effective means of reducing atmospheric levels of CO_2, and forestation and deforestation abatement efforts are already under way.

The terrestrial biosphere is estimated to sequester large amounts of carbon (approximately 2 billion metric tons of carbon per year). Research and development in this area seeks to increase this rate while properly considering all the ecological, social, and economic implications.

The Department of Energy's research is focused on integrating measures for improving the full life-cycle carbon uptake of terrestrial ecosystems, including farmland and forests, with fossil fuel production and use. The following ecosystems offer significant opportunity for carbon sequestration:

Forest lands. The focus includes below-ground carbon and long-term management and utilization of standing stocks, understory, ground cover, and litter.

Agricultural lands. The focus includes crop lands, grasslands, and range lands, with emphasis on increasing long-lived soil carbon.

Biomass croplands. As a complement to ongoing efforts related to biofuels, the focus is on long-term increases in soil carbon.

Deserts and degraded lands. Restoration of degraded lands offers significant benefits and carbon sequestration potential in both below-and above-ground systems. Boreal wetlands and peatlands. The focus includes management of soil carbon pools and perhaps limited conversion to forest or grassland vegetation where ecologically acceptable.

DOE's terrestrial sequestration research programs are being conducted in close collaboration with the U.S. Forest Service of the U.S. Department of Agriculture.

Ocean Sequestration

Carbon dioxide is soluble in ocean water, and through natural processes the oceans both absorb and emit huge amounts of CO_2 into the atmosphere.

It is widely believed that the oceans will eventually absorb most of the CO_2 in the atmosphere. However, the kinetics of ocean uptake are unacceptably slow, causing a peak atmospheric CO_2 concentration of several hundred years. The Energy Department's research programs, largely conducted by DOE's Office of Science, are exploring options for speeding up the natural processes by which the oceans absorb CO_2, and for injecting CO_2 directly into the deep ocean.

Enhancement of Natural Carbon Sequestration. One approach to enhancing the rate of CO_2 absorption in the ocean involves adding combinations of micronutrients and macronutrients to those ocean surface waters deficient in such nutrients. The objective is to stimulate the growth of phytoplankton, which are expected to consume greater amounts of carbon dioxide. When CO_2 is thus removed from the ocean surface waters, it is ultimately replaced by CO_2 drawn from the atmosphere. The extent to which the carbon from this increased biological activity is sequestered is unknown at this point, and would require additional research. Any R&D on natural enhancement would also require complete examination of potential environmental issues.

Direct Injection of CO_2. Technology exists for the direct injection of CO_2 into deep areas of the ocean; however, the knowledge base is not adequate to optimize the costs, determine the effectiveness of the sequestration, and understand the resulting changes in the biogeochemical cycles of the ocean.

To assure environmental acceptability, developing a better understanding of the ecological impacts of both ocean fertilization and direct injection of CO_2 into the deep ocean is a focus of DOE's carbon sequestration research. It is known that small changes in biogeochemical cycles may have large consequences, many of which are secondary and difficult to predict. Of particular concern is the effect of CO_2 on the acidity of ocean water.

Compared to terrestrial ecosystems and geologic formations, the concept of ocean sequestration is in a much earlier stage of development. A small level of funding in ocean sequestration research is providing leading researchers in this area an opportunity to develop the necessary scientific understanding on feasibility of ocean storage.

Advanced Concepts

Recycling and reuse of CO_2 from energy systems would be an attractive alternative to storage of carbon dioxide. Research into advanced concepts seeks to reduce the cost and energy required to chemically or biologically convert CO_2 into either commercial products that are inert and long-lived, or stable solid compounds.

Numerous conversion phenomena are found in nature, such as photosynthesis and mineral uptake to form carbonates. Carbon dioxide conversion research and development is trying to mimic these naturally occurring phenomena, but the task is challenging. Carbon dioxide is a highly stable compound containing a very low amount of chemical energy, and the natural conversion processes are slow and inefficient as a result.

The potential of chemical pathways is immense. For instance, the entire global emissions of carbon in 1990 could be contained as magnesium carbonate in a space 10 kilometers by 10 kilometers by 150 meters.

Concerning biological systems, incremental enhancements to the carbon uptake of photosynthetic systems could have a significant positive effect. Also, harnessing naturally occurring, non-photosynthetic microbiological processes capable of converting CO_2 into useful forms, such as methane and acetate, could represent a technology breakthrough. An important advantage of biological systems is that they do not require pure CO_2 and do not incur costs for separation, capture, and compression of CO_2 gas.

Research into advanced concepts for capture, reuse, and storage of CO_2 from energy production and utilization systems based on, but not limited to:

- biological systems;
- advanced catalysts for CO_2 or carbon monoxide conversion;
- novel solvents, sorbents, membranes and thin films for gas separation;
- engineered photosynthesis systems;
- non-photosynthetic mechanisms for CO_2 fixation;
- genetic manipulation of agricultural soils and trees to enhance CO_2 sequestering potential; and
- advanced decarbonization systems.

Measurement, Monitoring, and Verification

Measurement, monitoring, and verification, or MM&V, is defined as the capability to measure the amount of CO_2 stored at a specific sequestration site, to monitor the site for leaks or other deterioration of storage integrity over time, and to verify that the CO_2 is stored and poses no harm to the host ecosystem.

MM&V capability will ensure safe permanent storage, will reduce the risk associated with buying or selling credits for sequestered CO_2, and will help satisfy regulators and local government officials who must approve large sequestration projects. MM&V will also provide valuable feedback for continual refinement of injection and management practices.

DOE's sequestration programs are pursuing MM&V technology for a broad range of sequestration options including terrestrial ecosystems, geologic formations, and oceans. MM&V for terrestrial ecosystems includes 3-dimensional videography methods for modeling and tracking above-ground carbon and in-field technology to measure soil and other below-ground carbon.

In geologic sequestration, the programs are developing both below-ground and above-ground MM&V technology. Work in below-ground MM&V systems draws upon a significant capability developed for fossil resource exploration and production. Options include surface-to-borehole seismic, micro-seismic, and cross-well electromagnetic imaging devices. The area of above-ground MM&V is less mature, and is focused on detecting leaks from a geologic reservoir.

Measurement, monitoring and verification also includes the development of protocols and methodologies for calculating the net avoided CO_2 emissions from systems with carbon capture, specifically considering methods for replacing capacity.