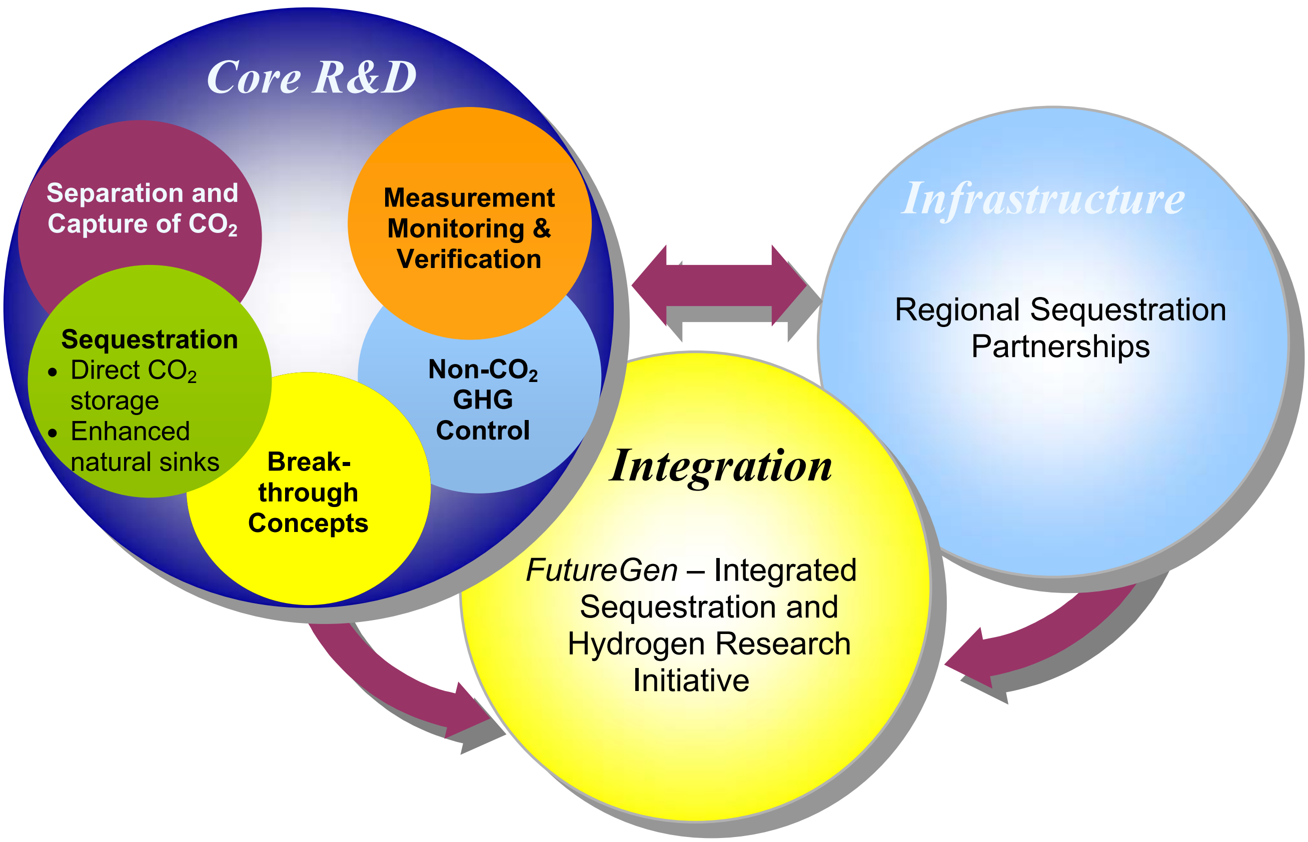
Carbon Sequestration

Technology Roadmap and Program Plan



March 12, 2003

U.S. DOE Office of Fossil Energy
National Energy Technology Laboratory

A MESSAGE TO OUR STAKEHOLDERS

On February 14, 2002 President Bush announced the **G**lobal **C**limate **C**hange **I**nitiative (**GCCI**) with the goal of significantly reducing the greenhouse gas intensity of the United States economy over the next 10 years, while sustaining the economic growth needed to finance investment in new, clean energy technologies. The GCCI calls for increased research and development investments to provide an improved basis for sound future decisions and for increased emphasis on carbon sequestration. In response to GCCI and related drivers, this document reflects important new developments.

- Measurement, monitoring, and verification (MM&V) of carbon sequestration has been prioritized along with carbon capture and carbon sequestration. Work in MM&V has been a part of the program from the outset, but the new structure represents increased emphasis.
- The program has adopted a revised strategic cost goal for carbon capture and sequestration: "create systems that capture at least 90% of emissions and result in less than a 10% increase in the cost of energy services." The revised goal puts the challenge for carbon sequestration in the context of minimizing the economic impact of greenhouse gas emissions mitigation.
- On November 21, 2002 Energy Secretary Spencer Abraham announced that the Department of Energy "intends to create a nationwide network of regional sequestration partnerships." The partnerships will seek to identify the most promising sequestration options in their area.
- The Program is collaborating with the National Academies of Science (NAS) to build a more robust portfolio of breakthrough concepts. In 2003 NAS conducted a workshop with experts from varied fields to identify specific and new R&D opportunities. The Program will use the results from the workshop in crafting a solicitation seeking breakthrough R&D projects.

> These partnerships - 4 to 10 across the country, each made up of private industry, universities, and state and local governments - will become the centerpiece of our sequestration program. They will help us determine the technologies, regulations, and infrastructure that are best suited for specific regions of the country.
>
> Energy Secretary Spencer Abraham
> November 21, 2002

Interaction with stakeholders is critically important to a successful R&D effort. In 2003 the program plans to engage stakeholder through the Second National Conference on Carbon Sequestration, the regional partnerships solicitation, the monthly carbon sequestration newsletter, conferences, and many other smaller outreach efforts.

This document is the current program vision of how to proceed in the development of carbon sequestration technology. It is both a roadmap and a program plan. The roadmap portion identifies RD&D pathways that lead to commercially viable carbon capture and sequestration systems. The program plan presents a course of action. Readers are invited to examine the document carefully and provide questions or comments to the contact persons listed on the back cover. Through a cooperative partnership of industry, academia, and government we have the best chance of success in developing viable carbon sequestration options.

GLOBAL CLIMATE CHANGE AND THE ROLE OF CARBON SEQUESTRATION

Alongside improved efficiency and low carbon fuels, carbon sequestration is a third option for greenhouse gas mitigation. It entails the capture and storage of carbon dioxide and other greenhouse gases that would otherwise be emitted to the atmosphere. The greenhouse gases can be captured at the point of emission, or they can be removed from the air. The captured gases can be stored in underground reservoirs, dissolved in deep oceans, converted to rock-like solid materials, or absorbed by trees, grasses, soils, or algae.

> ". . . 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

The Global Climate Change Initiative (GCCI) set forth by President George W. Bush calls for an 18% 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 GCCI goal. The GCCI also calls for a progress review relative to the goals of the initiative in 2012, at which time decisions will be made about additional implementation measures for mitigating greenhouse gas emissions. By focusing on greenhouse gas intensity (the ratio of greenhouse gas emissions to economic output) as the measure of success, this strategy promotes vital climate change R&D while minimizing the economic impact of greenhouse gas stabilization in the United States.

Strong evidence is emerging that indicates greenhouse gas emissions are linked to potential climate change impacts. Figure 1 shows that the concentration of carbon dioxide in the atmosphere has increased rapidly in recent decades, and the increase correlates to the industrialization of the world. In 1992, the United States and 160 other countries ratified the Rio Treaty which calls for " . . . stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." An appropriate level of greenhouse gases in the atmosphere is still open to debate, but even modest stabilization scenarios eventually require a reduction in worldwide greenhouse gas emissions of 50-90% below current levels.

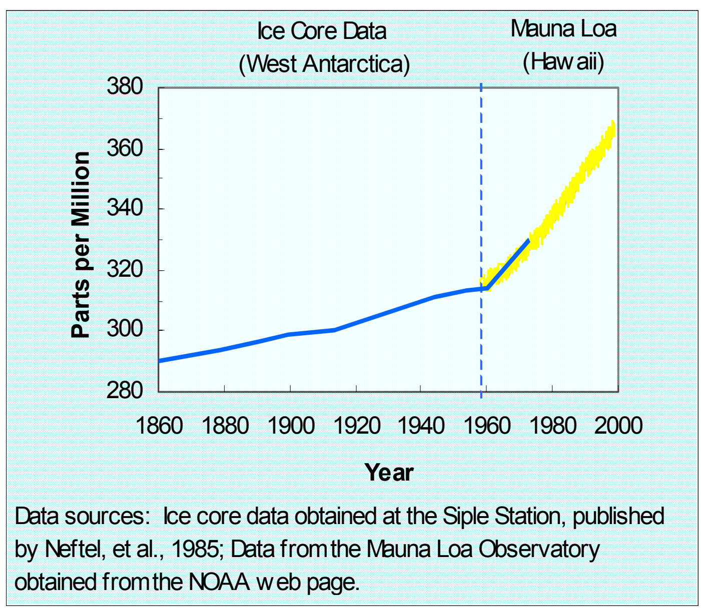


Figure 1. Atmospheric CO_2 Concentration is Increasing

In addition to national and international efforts, more than half of U.S. states have acted to pass voluntary or mandatory programs to limit net greenhouse gas emissions. For example:

Massachusetts: requires the six oldest power plants (40% of in-state generation) to reduce CO_2 emissions to 10% below the average 1997-1999 levels by 2006

Oregon: carbon emissions from new power plants must be at least 17% below the most efficient natural gas-fired plant operating in the U.S

New Hampshire: carbon dioxide (CO_2) from fossil fuel burning steam electric power plants must be reduced to 1990 levels by 2010

Also, California, New Jersey, New Hampshire and Wisconsin have established greenhouse gas registries, and there is a large body of pending greenhouse gas legislation at the state, county, and municipal levels.

PUBLIC BENEFITS THROUGH TECHNOLOGY DEVELOPMENT

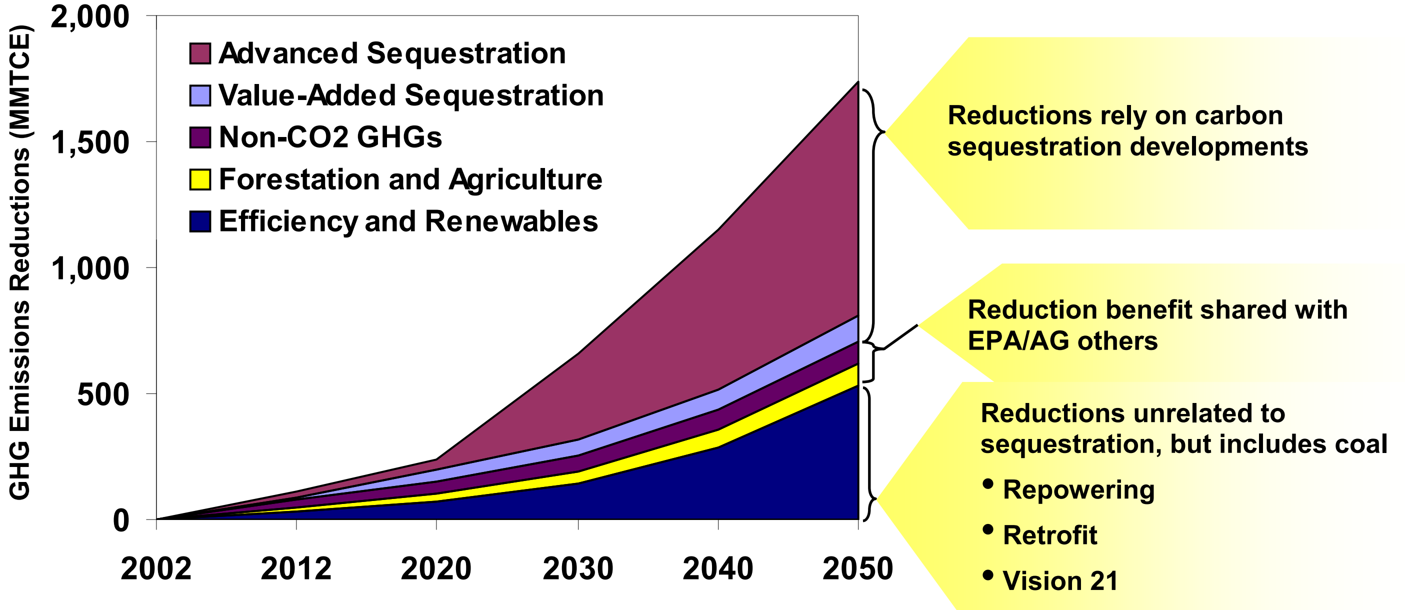
The Carbon Sequestration Program has performed an analysis of the role that carbon capture and storage can play in helping the United States and the world to stabilize and eventually reduce greenhouse gas emissions. The analysis shows that carbon sequestration can have a significant impact. On the capture side, roughly one third of the current U.S. greenhouse gas emissions come from power plants, oil refineries, and other large point sources, and that percentage will increase in the future with a trend toward increased refining and de-carbonization of fuels. On the storage side, the United States has vast forests and prairies, and is underlain by massive saline formations, depleting oil and gas reservoirs, and unmineable coal seams with the combined potential to store centuries worth of greenhouse gas emissions. Also, many options for CO_2 storage have the potential to provide value-added benefits. For example, tree plantings, no-till farming and other terrestrial sequestration options can prevent soil erosion and pollutant runoff into streams and rivers. CO_2 storage into depleting oil reservoirs and unmineable coal seams can enhance the recovery of crude oil and natural gas respectively while leaving a portion of the greenhouse gas sequestered. These value-added benefits have provided motivation for near term action and create interesting opportunities for integrated CO_2 capture and storage systems.

Hydrogen and Carbon Sequestration

Hydrogen-rich fuels and highly efficient electrochemical/mechanical drivers are at the center of many advanced energy system concepts. Leading technologies to produce hydrogen and other low-carbon fuels from natural gas and coal exhaust a highly pure stream of CO_2 as a natural part of their operation. These advanced systems represent an opportunity for low-cost CO_2 capture and provide a strong link between hydrogen energy systems and carbon capture and sequestration. **FutureGen**, a proposed $1 billion government/industry partnership to build and operate a coal-fired power generation and hydrogen production facility with advanced CO_2 capture and sequestration, will pursue this opportunity.

Figure 2 shows a reference case scenario for U.S. greenhouse gas emissions over the next fifty years compared to a reduced emissions scenario consistent with the Presidents GCCI goals through 2012 and a plausible stabilization scenario by mid century.   Current annual U.S. greenhouse gas emissions are 12% higher than they were in 1992, and the Energy Information Administration (EIA) forecasts that U.S. CO_2 emissions will increase by an additional 34% over the next 20 years [Annual Energy Outlook 2002]. The projected increase is more significant when one considers that in their analysis, EIA assumes significant deployment of new energy technology through 2020, for example, a fourfold increase in electricity generation from wind turbines, a doubling of ethanol use in automobiles, and a 25% decrease in industrial energy use per unit of output.   The need for greenhouse gas emissions reduction could be very large within a few decades and if potential for sequestration can be realized it can greatly reduce the cost of greenhouse gas emissions mitigation. For nearly any plausible scenario to greenhouse gas emissions stabilization, sequestration must account for at least 50% or more of the emissions reduction load.

Figure 2. Carbon Sequestration Technology is Needed to Reduce GHG Emissions



THE DOE CARBON SEQUESTRATION R&D PROGRAM

Recognizing the importance of carbon sequestration, the U.S. DOE established the Carbon Sequestration Program in 1997. The program, which is administered within the Office of Fossil Energy and by the National Energy Technology Laboratory, seeks to move sequestration technology forward so that its potential can be realized and it can play a major role in meeting any future greenhouse gas emissions reduction needs. The program directly implements the President's GCCI, 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.

The Carbon Sequestration Program encompasses all aspects of carbon sequestration. The program has engaged federal and private sector partners that have expertise in certain technology areas, for example U.S. Department of Agriculture and electric utilities in terrestrial sequestration, U.S. Geologic Survey and the oil industry in geologic sequestration, and the National Academies of Science in breakthrough concepts. A strong focus is placed on direct capture of CO_2 emissions from large point sources and subsequent storage in geologic formations. These large point sources, power plants, oil refineries, and industrial processes, are the foundation of our economy. Reducing net CO_2 emissions from these facilities complements efforts to reduce emissions of particulate matter, sulfur dioxide, and nitrous oxides and represent a progression toward fossil fuel production, conversion, and use with no detrimental environmental impacts. In addition, measurement, monitoring, and verification (MM&V) is emerging as an important cross-cutting component for CO_2 capture and storage systems, and terrestrial offsets are a vital component of cost-effective near-complete elimination of net CO_2 emissions from many large point sources.

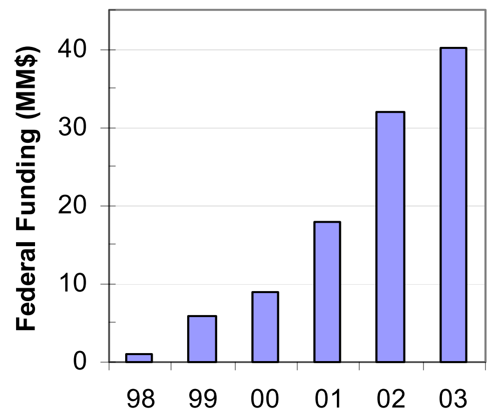


Figure 3. U.S. DOE Carbon Sequestration Program Budget

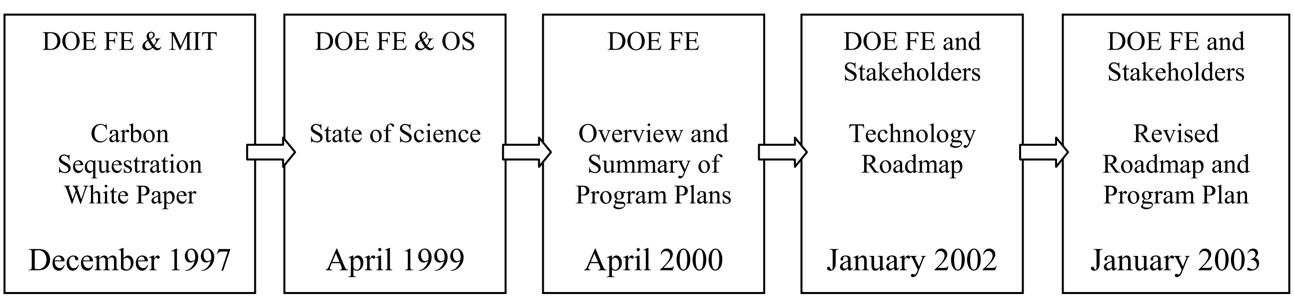


Figure 4. Roadmap Evolution

VISION STATEMENT

Possess the scientific understanding of carbon sequestration options and provide cost-effective, environmentally-sound technology options that ultimately lead to a reduction in greenhouse gas intensity and stabilization of overall atmospheric concentrations of CO_2.

Overarching Goals

- By 2006 develop instrumentation and measurement protocols for direct sequestration in geologic formations and for indirect sequestration in forests and soils that enable the implementation of wide-scale carbon accounting and trading schemes.
- By 2008, develop to the point of commercial deployment systems for advanced indirect sequestration of greenhouse gases that protect human and ecosystem health and cost no more than $10 per metric ton of carbon sequestered, net of any value-added benefits.
- By 2009, begin demonstration of advanced carbon storage in a geologic formation at large scale (>1MMTCO$_2$/year). Storage options include value-added (enhanced oil recovery, enhanced coal bed methane recovery, enhanced gas recovery) and non-value added (depleted oil/gas reservoirs and saline aquifers).
- By 2010 develop instrumentation and protocols to accurately measure, monitor, and verify both carbon storage and the protection of human and ecosystem health for carbon sequestration in terrestrial ecosystems and geologic reservoirs. MM&V systems should represent no more that 10% of the total sequestration system cost.
- By 2012, develop to the point of commercial deployment systems for direct capture and sequestration of greenhouse gas emissions from fossil fuel conversion processes that protect human and ecosystem health and result in less than a 10% increase in the cost of energy services, net of any value-added benefits.
- Enable sequestration deployments to contribute to the President's Global Climate Change Initiative goal of an 18% reduction in the greenhouse gas intensity of the United States economy by 2012.
- Provide a portfolio of commercial ready sequestration systems and also one to three breakthrough technologies that have progressed to the pilot test stage for the 2012 assessment under the Global Climate Change Initiative.
- By 2018, develop to the point of commercial deployment systems for direct capture and sequestration of greenhouse gas and criteria pollutant emissions from fossil fuel conversion processes that result in near-zero emissions and approach a no net cost increase for energy services, net of any value-added benefits.

Figure 5 shows how the different program elements contribute to the overarching program goal of commercial ready sequestration options. The Program is strongly focused on direct CO_2 capture from fossil fuel conversion systems and CO_2 sequestration in geologic formations. But also contains significant efforts in terrestrial and other indirect sequestration approaches. All are encompassed within the program elements shown in Figure 5. Major program efforts are described below.

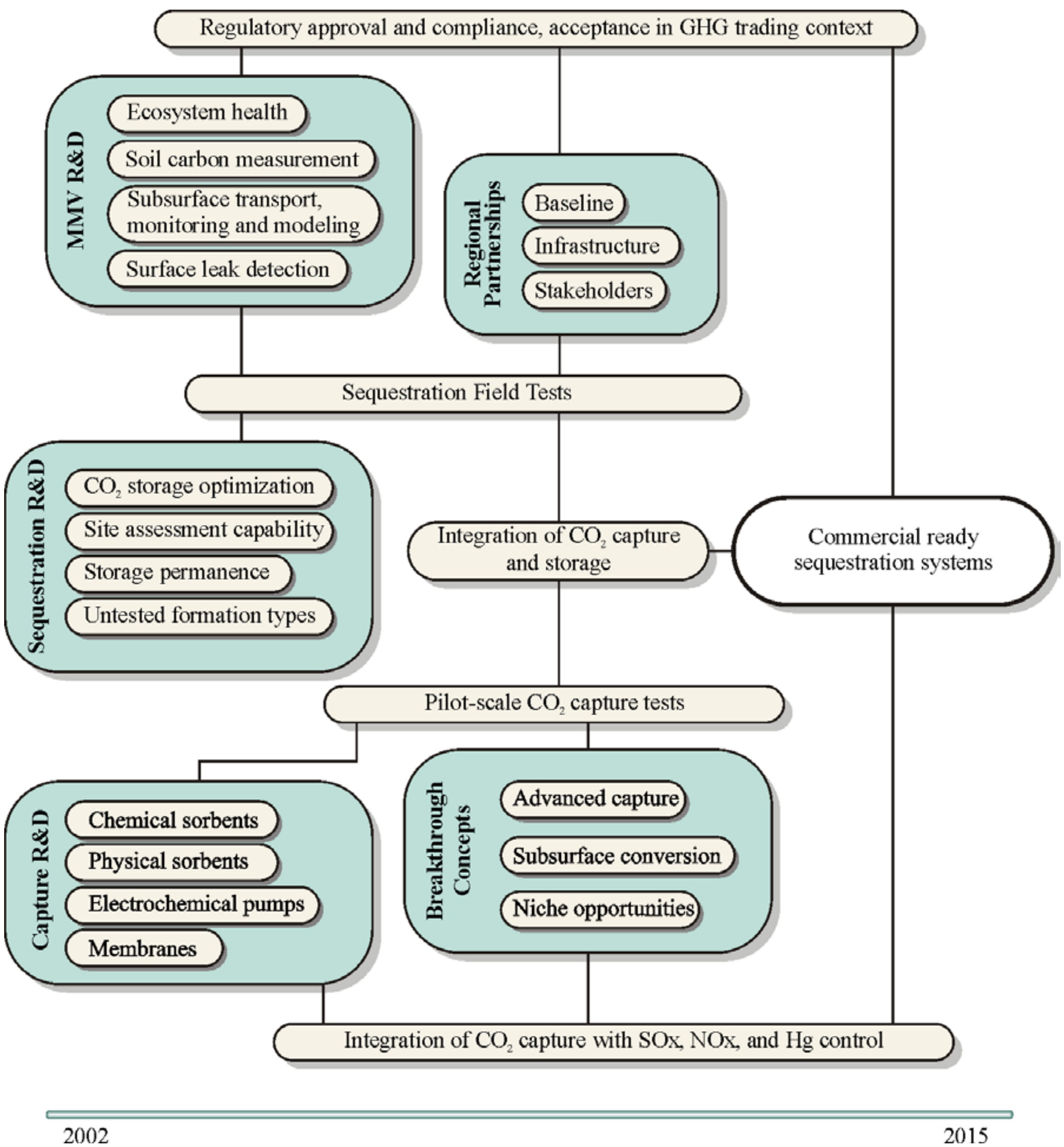
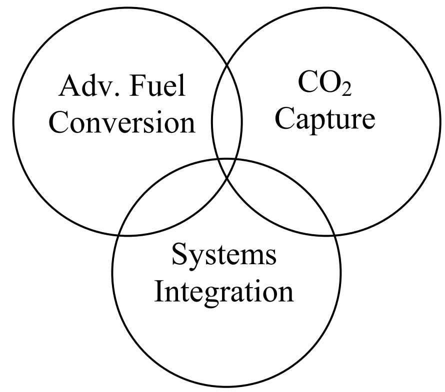


Figure 5. Carbon Sequestration Program Roadmap Diagram

CO_2 CAPTURE

The Carbon Sequestration Program funds capture R&D projects covering a wide range of technology areas including: amine absorbents, carbon adsorbents, membranes, sodium and other metal-based sorbents, electrochemical pumps, hydrates, and mineral carbonation. Presently, component performance is being evaluated at the laboratory or pilot scale. The majority of the work is funded through competitively awarded cost-shared projects with industry.



Research into a CO_2 capture technology occurs within the context of the energy conversion system(s) to which it is to be applied. There is a strong synergistic link between improved efficiency of fossil fuel conversion systems and carbon capture; the cost of carbon capture per unit of product is less for a more efficient process. Also, advanced fuel conversion technologies such as gasification, oxygen combustion, electrochemical cells, advanced steam reforming, and chemical looping produce a CO_2-rich exhaust stream that is highly amenable to CO_2 sequestration – or ready for transport and storage. Some CO_2 capture technologies can be applied to a wide range of CO_2-containing process streams. Others are more specialized. The program monitors developments in relevant research areas and evaluates the impact of advances on the priorities within the capture portfolio.

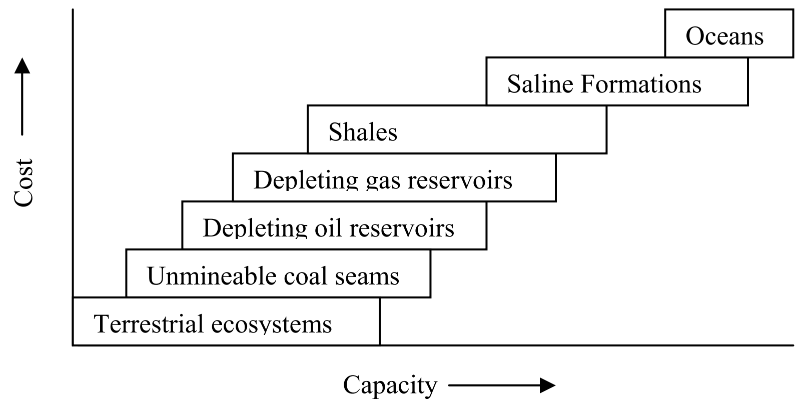
The cost and efficiency performance of CO_2 capture can be significantly improved through close consideration of systems integration issues, including integration of CO_2 capture and storage. For example, heat and pressure integration between CO_2 capture and the rest of the fossil fuel conversion systems can reduce parasitic steam and CO_2 recompression loads. Also, combining or integrating CO_2 capture with SO_x, NO_x, and mercury control can eliminate or lessen the need for scrubbers and other emissions abatement systems. Systems integration is being explored through laboratory and pilot scale experiments, and, ultimately in the commercial scale FutureGen demonstration.

SEQUESTRATION

This program element encompasses all forms of carbon storage, including storage in terrestrial ecosystems, geologic formations, and oceans. Through the development of optimized field practices and technologies, the program seeks to quantify and improve the storage capacity of all potential reservoirs and to expand the number and type of reservoirs in which carbon storage is commercially viable.

Increasing the carbon uptake in terrestrial ecosystems is highly correlated with fundamental agricultural and forestry goals of encouraging productive plant growth with sustainable harvests. The DOE sequestration program is focused on the integration of energy production, conversion, and use with land reclamation. Current projects include a large-scale demonstration of reforesting recently mined lands in Virginia, West Virginia, Kentucky and a smaller-scale demonstration integrating terrestrial sequestration with energy production by employing the use of coal combustion byproducts.

The program seeks to lower the cost and increase the capacity of the various CO_2 sequestration options



In the area of geologic sequestration, there are several types of formations in which CO_2 can be stored including: depleting oil reservoirs, depleting gas reservoirs, unmineable coal seams, saline formations, shale formations with high organic content, and others. Each type of formation has its own mechanism for storing CO_2 and a resultant set of research priorities and opportunities. The program has initiated a number of field tests where a small amount of CO_2 will be injected into a formation and its behavior studied. A goal of the Regional Partnerships initiative is to identify additional opportunities for both terrestrial and geologic sequestration field validation tests. Also, the program is investing in research facilities at NETL that will enable it to simulate the extreme environments in underground formations, conduct experiments, and develop a better understanding of the fundamental principles that will drive optimal CO_2 injection practices.

Compared to terrestrial ecosystems and geologic formations, the concept of ocean sequestration is in a much earlier stage of development. Ocean sequestration has huge potential as a carbon storage sink, but the scientific understanding to merit ocean sequestration as a real option is not available. A small level of funding is provided to leading researchers in this area to develop the necessary scientific understanding on feasibility of ocean sequestration. Work is focused on assessing the environmental impacts of CO_2 storage. The program is also funding laboratory experiments aimed at learning more about the basics of CO_2 drop behavior in an ocean environment and also the formation and behavior of CO_2 hydrates.

MEASUREMENT, MONITORING, AND VERIFICATION (MM&V)

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 unharmful 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.

The program is pursuing MM&V technology for a broad range of sequestration options including terrestrial ecosystems, geologic formations, and oceans. MM&V for terrestrial ecosystems includes 3D videography methods for modeling and tracking above ground carbon and infield technology to measure soil and other below ground carbon.

In geologic sequestration, the program is 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.

The MM&V program element also includes the development of protocols and methodologies for calculating the net avoided CO_2 emissions from systems with carbon capture, specifically considering and comparing different levels of parasitic losses and methods for replacing capacity.

BREAKTHROUGH CONCEPTS

The program is pursuing revolutionary sequestration approaches with potential for low cost, high permanence, and large global capacity. A guiding principal is to mimic and harness processes found in nature that convert CO_2 to another carbonaceous substance, for example photosynthesis and mollusk shell formation. A priority area of study is subsurface CO_2 conversion to enhance geologic sequestration.

The program is funding two major efforts in this area. First are facilities and experiments at the Carbon Sequestration Science Focus Area (CSSFA). The CSSFA uses in-house resources at NETL to conduct research in a number of sequestration areas with a focus on high technical risk concepts. A second and complementary effort is a collaboration with the National Academies of Science (NAS) to expand the number of projects from industry and academia. In 2003 NAS conducted an experts' workshop to identify R&D opportunities in the area of breakthrough concepts. The program will use the results from the workshop in crafting a solicitation for R&D projects. Once proposals are received, an NAS committee will evaluate the scientific, technical, engineering and environmental merits of each.

The Carbon Sequestration Science Focus Area at NETL

The CSSFA performs research and development in areas important to the program but with technical risk too high for industry. The following are recent success stories.

Turning a Conventional CO_2 Capture Technology into an Advanced One. **McMahan Gray** has developed a fundamentally straightforward method for implanting amines onto a variety of solid substrates. Conventional water/liquid amine capture systems require significant amounts of energy during the CO_2 absorption/desorption cycle. The solid amines fabricated with this new method have the potential to capture CO_2 with much less energy. The National Energy Technology Laboratory has filed a record of invention (DE09/966,570).

Understanding and Improving CO_2 Absorption on Coal. Early field tests of CO_2 storage in unmineable coal seams were producing results that departed from theoretical projections. **Karl Schroeder** has achieved a much greater predictive ability by properly incorporating the fact that coals increase in volume (swell) when they are exposed to CO_2 and absorb it onto their pore surfaces. Dr. Schroeder's insight will help practitioners to optimize CO_2 sequestration via enhanced coal bed methane.

REGIONAL SEQUESTRATION PARTNERSHIPS

The regional diversity of CO_2 sources and storage options calls for a diverse portfolio of strategies for carbon management. The Program seeks to engage local government agencies and non-governmental organizations, along with the research community and private sector participants, in a number of Regional Sequestration Partnerships centered in areas of the country with potential for CO_2 capture and storage.

These partnerships will promote the development of a framework and infrastructure necessary for the validation and deployment of carbon sequestration technologies. The partnerships will baseline the region for CO_2 sources and sinks and will establish MM&V protocols. They will also address regulatory, environmental, and outreach issues associated with priority sequestration opportunities in the region. In FY 2003 the program plans to make 4-10 phase 1 regional partnership awards. In FY 2005, the program plans to advance to a second phase in which sequestration opportunities identified by the Phase I regional partnerships could serve as settings for technology field validation tests.

FUTUREGEN – AN INTEGRATED SEQUESTRATION AND HYDROGEN RESEARCH INITIATIVE

Contingent upon funding approval, in FY 2003 the Program plans an Integrated Sequestration and Hydrogen Research Initiative that couples CO_2 separated and captured from a coal-fired power plant with sequestration in a geologic formation. The project will focus on large systems, of greater that one million metric tons of CO_2 sequestered per year, and concepts where CO_2 capture and geologic sequestration are integrated. The project is a logical and required extension of the base Carbon Sequestration R&D Program and will, if successful, achieve the following:

- Design, construct, and operate a nominal 275-megawatt (net equivalent output) prototype plant that produces electricity and hydrogen with near-zero emissions. The size of the plant is driven by the need for producing commercially-relevant data, including the requirement for producing one million metric tons per year of CO_2 to adequately validate the integrated operation of the gasification plant and the receiving geologic formation.

- Sequester at least 90 percent of CO_2 emissions from the plant with the future potential to capture and sequester nearly 100 percent.

- Prove the effectiveness, safety, and permanence of CO_2 sequestration.

- Establish standardized technologies and protocols for CO_2 MM&V.

- Validate the engineering, economic, and environmental viability of advanced coal-based, near-zero emission technologies that by 2020 will: (1) produce electricity with less than a 10% increase in cost compared to non-sequestered systems; (2) produce hydrogen at $4.00 per million Btus (wholesale), equivalent to $0.48/gallon of gasoline, or $0.22/gallon less than today's wholesale price of gasoline.

NON-CO_2 GREENHOUSE GASES

Because non-CO_2 greenhouse gases (e.g., methane, N_2O, and high global warming potential gases) have significant economic value, emissions can often be captured or avoided at low net cost. The program is focused on areas where non-CO_2 greenhouse gas abatement is integrated with energy production, conversion, and use. Two projects are currently being funded: (1) minemouth ventilation methane mitigation [Consol, Inc.] and (2) impermeable membranes for landfill gas recovery [IEM, Inc.]. The Program is working with the United States Environmental Protection Agency (EPA) to assess the role that non-CO_2 greenhouse gas emissions abatement actions can play in a nationwide strategy for reducing greenhouse gas emissions intensity. The Program is also working with EPA to identify priority areas for research and development.

EDUCATION AND OUTREACH

The notion of capturing and sequestering carbon dioxide and other greenhouse gases is relatively new, and many people are unaware of its role as a greenhouse gas reduction strategy. Increased education and awareness are needed to achieve acceptance of carbon sequestration by the general public, regulatory agencies, policy makers, and industry and thus enable future commercial deployments of advanced technology. The following activities highlight the program's education and outreach efforts:

- Carbon Sequestration Webpage at the NETL site
- Monthly sequestration newsletter
- The 2002 Sequestration Technology Roadmap
- The First National Conference on Carbon Sequestration (May 2001) and the Second National Conference on Carbon Sequestration (planned for May 2003)

In addition the program management team participates in technical conferences through presentations, panel discussions, break out groups, and other formal and informal venues. These efforts expose professionals working on other fields to the technology challenges of sequestration and also enable examination of some of the more detailed issues underlying the technology. Examples include the Terrestrial Carbon Sequestration "Hands-On" Workshop for the Appalachian Coal & Electric Utilities Industries held in November 2001 and sequestration-related symposia organized at recent meetings of the American Geophysical Union and American Association for the Advancement of Science.

The Carbon Sequestration Newsletter

Started in July 2001, the newsletter provides brief summaries of sequestration-related news, events, recent publications, and legislative activity. Subscription has grown to over 800. In August of 2002, NETL issued the annual newsletter index, which is a useful tool for finding articles and news pieces over the past year. Back issues and the index can be downloaded from the NETL site.

You can register to receive the newsletter (it is free). Go to:

http://www.netl.doe.gov/coalpower/sequestration/index.html

and click on "get the news."

As with any new technology, there are environmental issues associated with carbon sequestration that need to be explored, understood, and addressed. The level of uncertainty is higher for some sequestration options than for others. A significant portion of the program's R&D portfolio is aimed at improved understanding of potential environmental impacts. In concert with R&D, the program seeks to engage NGO's, federal, state, and local environmental regulators to raise awareness of what the program is doing in this area, and the priority it places on systems that preserve human and ecosystem health. Some of the program's R&D projects have their own outreach component. For example, the cost-shared project with the Nature Conservancy on measuring, monitoring, and verification in terrestrial ecosystems has helped the program to engage Non-Governmental Organizations and the environmental community. Also, the Regional Partnerships will enhance technology development but also engage regulators, policy makers, and interested citizens at the state and local level. Successful outreach entails two-way communications, and the program will consider concerns voiced at outreach venues and continually assess the adequacy and focus of the current R&D portfolio.

INTERNATIONAL COLLABORATION

Recognizing that the needs for new science and technologies to reduce greenhouse gas emissions is a global concern, the Carbon Sequestration Program is deeply engaged in building international collaboration and partnerships throughout the world. The following are prominent examples of the program's work with international entities. As global interest and funding in carbon sequestration research increases, these collaborations will likely expand

International Energy Agency The DOE is a participating member in the International Energy Agency's Greenhouse Gas Research and Development Programme (IEA/GHG). The program was started in 1991 and is arguably the most well respected international effort in the greenhouse gas R&D arena. It is funded by 18 international members including the European Union, Australia, Canada, Italy, Japan, Norway, and eight private sector sponsors. The Programme evaluates greenhouse gas mitigation technologies; disseminates information via a bi-monthly newsletter "Greenhouse Issues" and a web-site; and organizes international expert workshops and conferences, most prominently the biannual Greenhouse Gas Technology Conference. Information can be found at http://www.ieagreen.org.uk/

The Carbon Capture Project (CCP) In 2001, the DOE awarded a cooperative agreement with British Petroleum (BP) Corporation to develop innovative CO_2 capture technologies. BP is the operating agent for the CCP, a consortia of eight major international energy companies (ChevronTexaco, Norsk Hydro, ENI, PanCanadian, Royal Dutch/Shell, Statoil and Suncor Energy) that are collectively funding the project from the industry side. The CCP aims to develop new, breakthrough technologies to reduce the cost of carbon dioxide separation, capture, transportation and sequestration from fossil fuel combustion streams by at 50% for existing energy facilities, and by 75% for new energy facilities, by the end of 2003 compared to currently available alternatives. Additional information can be found at http://www.co2captureproject.org/

Canada The US DOE Sequestration Program is co-funding, along with Pan Canadian Resources, Dakota gasification, and the Department of Natural Resources of Canada, a project to sequester carbon as a part of an enhanced oil operation in Weyburn, Canada in southeastern Saskatchewan. The collaboration was made possible through a negotiated Annex to the provisions of the Implementing Arrangement between U.S. DOE and the Department of Natural Resources of Canada for Cooperation in the Area of Fossil Fuels, signed on February 1, 2000. Additional information can be found at http://www.ieagreen.org.uk/weyburn4.htm

Norway Roughly one million metric tons per year of vented CO_2 from a natural gas processing platform in the north sea is being captured and injected into the Utsira saline aquifer formation. The Sliepner project was spearheaded by Statoil which sought to take advantage of a Norwegian CO_2 emissions tax credit. Working with the IEA/GHG R&D Programme, the carbon sequestration program has provided funding for the Saline Aquifer CO_2 Storage (SACS) project--a robust measurement, verification and transport modeling activity to compliment and enhance the injection experiment. This work will ensure that as much as possible is learned. Additional information can be found at http://www.ieagreen.org.uk/sacshome.htm

CARBON SEQUESTRATION TECHNOLOGY ROADMAP AND SUPPORTING PROGRAM ACTIVITIES

The following tables provide more detailed information about sequestration technology pathways and supporting program activities.

Table 1 is a top-level roadmap plan for four primary technology thrusts: CO_2 capture, sequestration, MM&V, and breakthrough concepts. For each technology thrust, Table 1 presents goals, pathways, and metrics for success.

Tables 2, 3, and 4 present Level II roadmaps for capture, sequestration, and MM&V. These tables describe the current status the pathways within each technology thrust area, present a list of R&D opportunities specific to each pathway, and also present crosscutting R&D opportunities. Program goals that apply to each pathway are defined, and a list of relevant projects from the program's R&D portfolio aimed are presented.

Table 5 presents four new program initiatives: the collaboration with the National Academies of Science (NAS), the regional partnerships initiative, *FutureGen* – an integrated sequestration and hydrogen research initiative, and the MM&V program. The initiatives are described and metrics for success defined for each.

A Level II roadmap table is not presented for Breakthrough Concepts. A major focus of the NAS collaboration and the subsequent solicitation will be to identify pathways and projects in that area. The 2004 Roadmap will supply a Level II table for breakthrough concepts based on the results of the NAS workshop.

A Level II roadmap table is also not presented for Non-CO_2 greenhouse gas abatement. Results from ongoing collaborative work with the U.S. EPA will be presented in next year's roadmap.

Table 1. Top Level Carbon Sequestration Roadmap

	Goals	Pathways	Metrics for Success		
			2004	**2007**	**2012**
Capture	• Lower the capital cost and energy penalty associated with capturing CO_2 from large point sources	• Post-combustion capture • Oxygen combustion • Pre-combustion capture • Chemical looping	Retrofits: 30% reduction in capital cost and energy load below 2002 technology	New builds: 75% reduction in capital cost and energy load below 2002 technology	10% increase in cost of energy proven for direct capture concept
Sequestration	• Expand the number and type of carbon sequestration opportunities in the United States and the world • Lower the cost and optimize the value-added benefits associated with CO_2 storage • Develop field practices to minimize seepage from geologic storage sites. • Develop management practices to promote permanence at terrestrial sequestration sites • Develop capability to assess capacity for carbon storage	• Depleting oil reservoirs • Unmineable coal seams • Saline formations • Enhanced terrestrial uptake • Ocean fertilization • Novel geologic formations • Ocean injection	Demonstrate net CO_2 storage in depleting oil reservoir of 10,000 scf CO_2 per barrel of oil recovered (increase from typical current value of 2,000 scf CO_2/bbl)	Demonstrate net CO_2 storage in an unmineable coal seam of 3 scf CO_2 per scf CBM recovered Demonstrate CO_2 injection into saline formations via horizontal or multilateral wells	Global CO_2 seepage verified at less than 0.01% per year
MM&V	• Develop technologies to accurately baseline terrestrial ecosystems, geologic formations, and ocean systems • Develop technologies to assess ecological impacts of carbon storage • Develop capability to detect leaks or deterioration in CO_2 storage • Develop methods for calculating net avoided emissions from CO_2 capture, transport, and storage systems	• Advanced soil carbon measurement • Remote sensing of above-ground CO_2 storage and leaks • Detection and measurement of CO_2 in geologic formations • Fate and transport models for CO_2 in geologic formations • Ecosystem flux models	Instrumentation & measurement protocols for geologic formations, forests, and soils that enable carbon accounting and trading and maximize credits achievable	Capability to ensure the permanence of GHG storage in geologic, ocean and terrestrial sinks and to assess the protection of human and ecosystem health	MMV represents no more than 10% of total sequestration cost
Breakthrough concepts	• Develop revolutionary approaches to carbon capture and storage that have the potential to address the level of reductions in greenhouse gas emissions consistent with long term atmospheric stabilization	• Advanced CO_2 capture, including biochemistry and enzymes • Bio-accelerated sequestration subsurface • CO_2 neutralization subsurface • Niches –circumstances where it is very easy or convenient to sequester some carbon	Achieve orders of magnitude improvement in mineralization reaction rates and energy needs at pilot scale	Identify breakthrough direct capture and storage with potential for less than 10% increase in cost of energy based upon lab scale results	Lab scale concept for indirect capture/conversion at 10 $/ton 10% increase in cost of energy proven for direct capture concept

Table 2. Level II - CO_2 Capture Roadmap and Program Plan

Roadmap				Plan	
Path ways	Current Technology Status	R&D Opportunities		Pathway-level Goals	Supporting Program R&D Projects
		Pathway-specific	Cross-cutting		
Pre-combustion de-carbonization	10 oxygen-fired gasifiers in operation in the United States today. Syngas from an oxygen-fired gasifier can be shifted to provide a stream of primarily H_2 and CO_2 at 400-800 psi. Glycol solvents can capture CO_2 and be regenerated via flash (no steam use) to produce pure CO_2 at 15-25 psi.	• Advanced amine absorption • Develop advanced physical or chemical absorption technology • Improved CO_2/H_2 membranes	Heat and pressure integration with other system components. Integration/ combination with NO_x, SO_x, Hg, and particulate matter control Hybrid oxyfuel/post combustion capture systems Integrate capture and geologic storage	**2007** 75% reduction in capital cost and energy load for CO_2 capture from new builds compared to 2002 technology	• Selective ceramic membrane [MPT] • CO_2 hydrate capture process [Bechtel] • High-temperature polymer membrane [INEEL, LANL]
Oxygen-fired combustion	No oxygen-fired PC plants in commercial operation. Current minimum CO_2 recycle is 5 lbs CO_2 per lb coal feed. 90% pure CO_2 is produced from the boiler at 10-15 psi. Oxygen combustion requires roughly three times more oxygen per kWh of electricity generation than gasification.	• O_2-selective membranes • Advanced cooling cycles • Compact boilers and turbines that can operate at high temperature and pressure		**2004** pilot scale demo of potential for 75% reduction in CO_2 recycle requirements	• Advanced oxyfuel boiler design [Praxair, Alstom Power – parallel projects]
Post-combustion capture	300 GW of PC boiler capacity in the United States. Flue gas from a PC boiler is exhausted at 10-15 psi and contains 12-18 volume percent CO_2. Amine scrubbing with CO_2 compression to 1200 psi costs roughly 2000 $/kW and reduces the net power plant output by 12.5%.	• Advanced amine absorption • Physical sorbents • CO_2 selective membranes • Sorbent/membrane • Advanced gas/liquid contactors		**2004** pilot scale demo of potential for 30% reduction in steam consumption per CO_2 captured below 2002 amine technology.	• Sodium/magnesium-based chemical sorbents [RTI] • Electrochemical pump [CCP, CSSFA] • Amine enriched adsorbents [CSSFA] • Carbonate-based CO_2 capture [CSSFA]
Advanced conversion	There are a limited number of promising ideas in this area. None of them are at the commercial or demonstration phase.	• Chemical looping		**2007** pilot scale demo of potential for capital and operating cost 20% higher than a 2002 PC boiler.	• Metal oxide materials for chemical looping fuel conversion process [TDA research]

Table 3. Level II - Sequestration Roadmap and Program Plan

	Roadmap			Plan	
	Current Status	R&D Opportunities		Pathway-level Program Goals	Supporting Program R&D Projects
		Pathway specific	Crosscut		
Depleting oil reservoirs	32 million tons of CO_2 per year injected into depleting oil reservoirs in the U. S. as a part of enhanced oil operations, 10 % from anthropogenic sources. Current practices are not directed toward optimizing CO_2 storage, typical storage rate is 2,000 scf CO_2 per bbl oil recovered.	• Modeling and testing for maximum long-term storage of CO_2 with EOR	Integrated database of domestic saline formations, depleting and depleted oil and gas wells, an coal seams containing data related to CO_2 storage potential Integrate knowledge and understanding from sequestration field test and capacity modeling with transport modeling efforts in MM&V Develop methodologies and strategies for produced water	**2004** Demonstrate net CO_2 storage in depleting oil reservoir of 10,000 scf CO_2 per barrel of oil recovered (5-fold increase over current operations)	• Develop a three dimensional model of an existing depleting oil field to assess co-optimization of CO_2 storage and oil/gas recovery [LBNL]
Unmineable coal seams	Coal bed methane is the fastest growing source of domestic natural gas supply, 1.6 TCF produced in 2001. No commercial deployments of CO_2-enhanced CBM recovery. CO_2 must compete with nitrogen as an enhancing agent.	• Improve understanding of injection of CO_2 and CO_2/N_2 mixtures • Understand swelling in domestic coals • Advanced injection well configuration		**2007** Demonstrate net CO_2 storage in an unmineable coal seam of 3 scf CO_2 per scf CBM recovered (2-fold increase over current operations)	• Field experiment in San Juan, NM, 4 million scf CO_2 per day [ARI/Burlington Resources] • Field test of slant hole drilling, Southern Virginia, ## scf CO_2 per day [Consol, Inc.] • CO_2 storage capacity model of Black Warrior region in Alabama [AGS]
Saline formations	Several large saline formations underlie the United States, but there is no injection of CO_2 into them. One million tons CO_2 per year is being injected in the saline formation at the Sliepner natural gas production field in the North Sea. A significant body of data on domestic brine formations has been compiled by NETL, the University of Texas at Austin, and others.	• CO_2 flow modeling for diverse formations • Studies of CO_2 in brine chemical mineral systems • Horizontal and multilateral wells for improved CO_2 injectivity		**2007** Demonstrate CO_2 injection into domestic saline formations via horizontal or multilateral wells	• Perform detailed CO_2 storage capacity assessments for (1) the Mt. Simon formation underlying the Midwestern U.S. [AEP, BCL] (2) the Frio Brine formation near Houston, TX. [LBNL], and (3) formations underlying the Colorado Plateau [University of Utah] • Investigate hydraulic fracturing to improve permeability [Texas Tech University] • Study CO_2 carbonation reactions in simulated brine environments [CSSFA]
Novel geologic formations	Promising but untested reservoir types have significant carbon storage capacity and the potential for value-added hydrocarbon production with CO_2 storage.	• depleting gas reservoirs • organically rich shales		**2012** Demonstrate the viability of CO_2 storage in one new type of geologic formation	• Analyze Devonian Black Shales in Kentucky for CO_2 storage capacity [University of Kentucky]

Table 3. Level II - Sequestration Roadmap and Program Plan *(continued)*

	Roadmap			Plan	
	Current Status	R&D Opportunities		Pathway-level Program Goals	Supporting Program R&D Projects
		Pathway specific	Crosscut		
Enhanced terrestrial uptake	Currently terrestrial uptake offsets roughly one third of global anthropogenic CO_2 emissions. The uptake from domestic terrestrial ecosystems is expected to decrease 13% over the next 20 years as northeastern forests mature. Opportunities for enhanced terrestrial include 1.5 MM acres of land damaged by past mining practices, 32 MM acres of CRP farmland, and 120 MM acres of pastureland.	• Forestation and reforestation • Agricultural practices to increase soil carbon • Integration of fossil energy production and use with land reclamation and productivity improvement	Understand ecosystem level interactions between biosphere and , geologic reservoirs. Determine role of oceans in global ecosystem dynamics.	**2007** Reclaim 100,000 acres of damaged land to increase carbon uptake	• Lab-scale assessment of solid waste soil amendment effects on soil carbon, design of pilot test [ORNL, PNNL] • Demonstrate and assess the life-cycle costs of integrating electricity production with enhanced terrestrial carbon sequestration at TVA's 2,558 MW Paradise Station. Demonstration area is 100 acres. [TVA, EPRI] • Demonstrate reforestation and enhanced carbon sequestration on 500 acres mined lands in Kentucky. [UK, USDA Forest Service]
Ocean fertilization	Experimental results and observed surges in phytoplankton growth after dust clouds pass over certain ocean regions indicate that increasing the concentration of iron and other macronutrients in certain ocean waters can greatly increase the growth of phytoplankton and thus CO_2 uptake. Ocean fertilization remains highly controversial because of uncertainty surrounding other changes it may cause.	• Establish the scientific knowledge base needed to understand, assess, and optimize ocean fertilization • Develop effective macronutrient seeding methodologies • Assess long-term CO_2 fate and flux		Improved scientific understanding of this option	
Ocean injection	No pilot or commercial applications. Small-scale experiments have been carried at the MBARI. Also NETL has the capability to simulate deep ocean conditions and has been conducting experiments on CO_2 droplet stability. A conceptual design of infrastructure for CO_2 transport and injection has been completed by MTI.	• Formation of CO_2 hydrates as a stable form of storage • CO_2 plume dynamics • Environmental impacts of increased CO_2 concentrations in deep ocean water		Improved scientific understanding of this option	• Synthesize CO_2/H_2O hydrates and observe small quantities on the floor of the Monterey Bay [LLNL, NRL, MBARI] • Study CO_2 droplet behavior in simulated deep ocean environments [CSSFA]

Table 4. Level II – MM&V Roadmap and Program Plan					
Roadmap				**Plan**	
	Current Status	R&D Opportunities: Pathway Specific	R&D Opportunities: Cross cut	Pathway-level Goals	Supporting Program R&D Projects
Terrestrial Ecosystems	Roughly 8 mmt of carbon sequestered in terrestrial ecosystems was traded in 2002, requiring preliminary estimations of baseline carbon stocks and projected storage. Current on-the-ground measurements are accurate within plus or minus 5-30% and can cost as little as $1/ton carbon offset.	• Reduce cost of baselining • Remote sensing of above ground carbon • In-field technology for soil carbon measurement • Correlations between soil and above ground carbon • Technologies for measuring inorganic soil carbon	Universal MM&V standards for diverse sequestration systems Develop protocols for using advanced MM&V technologies in commercial applications Understand regulatory analogs for geologic and ocean carbon storage Assess the degree to which risk is inhibiting market use of sequestration for GHG emissions abatement	**2004** Improved accuracy of baseline and inventory MMV technology to enable verifiable credits and carbon accounting **2007** Capability to ensure permanence and protection of human and ecosystem health **2012** MMV represents no more than 10% of total sequestration cost	• Use aerial videography to construct geo-referenced mosaics and 3D terrain. [Nature Conservancy] • Develop advanced laser-induced breakdown spectroscopy device for infield detection of soil carbon [LANL] • Develop capability to use genetic diversity analyses as an indicator of soil carbon accumulation [LANL]
Geologic Formations	Geophysical techniques can remotely characterize oil reservoir properties and changes post CO_2 injection. In July 2002, Ontario Power Generation bought 6 million tons of CO_2 emissions credits from Blue Source LLC which provided the emission reductions from oilfield carbon sequestration projects in Texas, Wyoming and Mississippi. Advanced technologies for higher resolution CO_2 detection are being tested at several sites including the Sliepner, Weyburn, and West Pearl Queen, and Lost Hills reservoirs.	• Surface to borehole seismic • Micro-seismic • Cross well electromagnetic • Electrical resistance tomography • CO_2 tracers			• Design and assess advanced CO_2 imaging technology [LBNL] • Inject 3,000 tons of CO_2 into the West Pear Queen Oil reservoir and measure CO2 migration [SNL, LLNL] • Measure and study the movement of CO_2 at the commercial EOR operation in Weyburn, Canada [Dakota Gasification] • Field test CO_2 tracer chemicals at injections sites in New Mexico and California [CSSFA, LBNL] • Study natural CO_2 deposits in the United States to evaluate safety and permanence of CO_2 storage [ARI]
Oceans	Established protocols for measuring dissolved organic and inorganic carbon in ocean water have been developed as a part of varied studies of ocean ecosystems.	• Capability to image hydrate formation • Advanced tools for monitoring seawater chemistry and biological impacts in-situ • Diffraction • NMR spectroscopy • Raman spectroscopy		**2007** Develop systems to measure carbon storage and human and ecosystem health impacts for ocean sequestration experiments	• Sea floor gravity survey of the Sliepner field to monitor CO_2 migration [UCSD]

Table 5. Major New Initiatives					
Initiative	**Description**	**Applicable Technology Development Areas**	**Metrics for Success**		
			2004	**2007**	**2012**
Collaboration with the National Academies of Science	In 2003 NAS conducted an experts' workshop to identify R&D opportunities in the area breakthrough concepts. The program will use the results from the workshop in crafting a solicitation for R&D projects. Once proposals are received, an NAS committee will evaluate the scientific, technical, engineering and environmental merits of each.	• Breakthrough Concepts	Award multiple promising R&D projects that represent fundamentally new areas for the carbon sequestration program	2 breakthrough direct capture projects show potential for a 10% increase in energy based on lab-scale results	• 1 concept with enough promise to play a role in the 2012 GCCI technology assessment
Regional Sequestration Partnerships	Partnerships will evaluate options and potential opportunities for CO_2 capture, transport, and storage in the defined region and investigate monitoring and verification requirements and regulatory, environmental, and outreach issues.	• Capture • Sequestration • MM&V • Education and Outreach	4-10 cost-shared projects up and running	Phase II awards for technology validation	• Deployment of 1-3 commercial scale carbon sequestration systems that were initiated as a result of regional partnership activities
FutureGen Integrated Sequestration and Hydrogen Research Initiative	Contingent upon funding approval, in FY 2003 the Program plans to release a solicitation for an Integrated Sequestration and Hydrogen Research Initiative in which CO_2 is separated and captured from coal-fired power plant and subsequently sequestered in a geologic formation. The project will focus on large systems, greater that one million tons of CO_2 sequestered per year, and concepts where CO_2 capture and geologic sequestration are integrated.	• Capture • Sequestration • MM&V	Several industry teams rigorously evaluate sequestration options and submit a proposal DOE makes one or more awards for design phase	Demonstration project(s) advance to construction phase	• Demonstrate advanced CO_2 capture technology at large scale • Develop best field practices for geologic CO_2 sequestration • Provide an opportunity to test and refine MMV systems
MM&V Program	Nexus of MMV efforts will contribute to the growing emphasis on MMV consistent with the GCCI. Focus on surface measurement and leak detection. Both the Regional Partnerships and Integrated Demonstration Program have strong MMV aspects.	• Cross cuts all areas		Tools developed enable measurement and verification at reduced cost and improved accuracy	• Internationally accepted protocols

RESOURCE REQUIREMENTS

Figure 6 shows the estimated resources needed to pursue the opportunities identified in the technology roadmap and achieve the program goals. The base program funding is estimated at roughly $50 MM per year, with slightly more between 2006 and 2010. The regional partnerships will require an initial investment but are structured to become self-sustaining after five years. The FutureGen Integrated Sequestration and Hydrogen Research Initiative will require a significant investment. This is due to the fact that large deployments are needed to prove out new technologies and that a portfolio of projects are needed to validate the different types of CO_2 point sources and storage options.

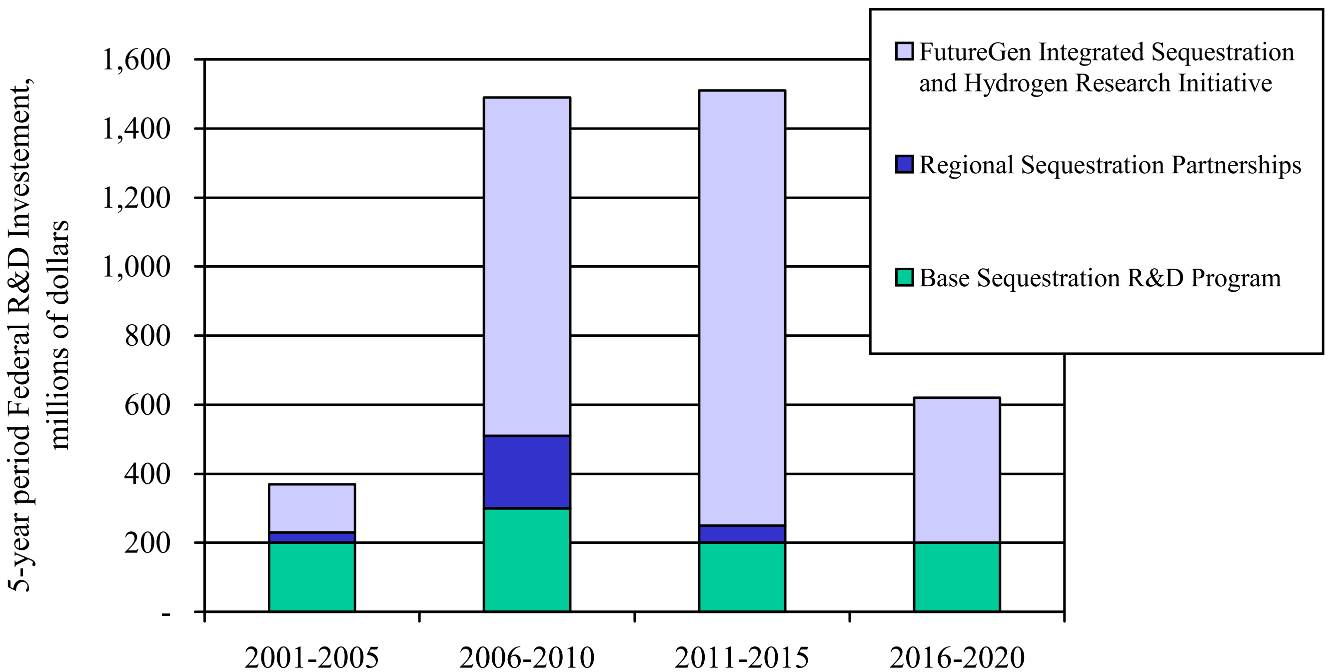


Figure 6. Funding Requirements of the Carbon Sequestration Program

If you have any questions, comments, or would like more information about DOE's Carbon Sequestration Program please contact the following persons:

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