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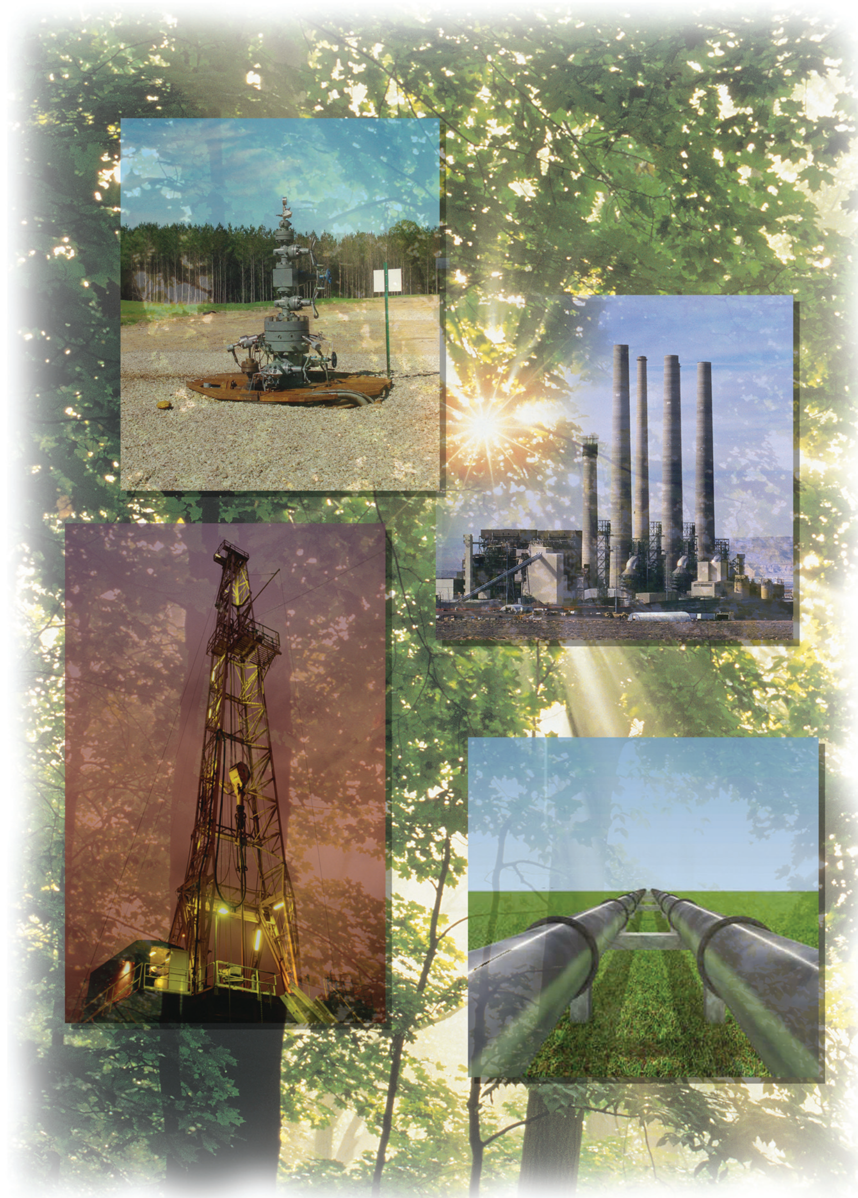
Carbon Sequestration Program: Technology Program Plan



Enhancing the Success of Carbon Capture and Storage Technologies

Applied Research and Development from Lab- to Large-Field Scale

February 2011

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

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List of Acronyms and Abbreviations

Acronym/Abbreviation	Definition
2-D	Two-Dimensional
3-D	Three-Dimensional
AR	Advanced Research
ARRA	American Recovery and Reinvestment Act of 2009
ASTM	American Standard Test Method
BLM	Bureau of Land Management
BPM	Best Practice Manual
CBM	Coalbed Methane
CCPI	Clean Coal Power Initiative
CCS	Carbon Capture and Storage
CCSI	Carbon Capture and Storage Initiative
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSLF	Carbon Sequestration Leadership Forum
$CaCO_3$	Calcium Carbonate
DOE	U.S. Department of Energy
DOI	U.S. Department of Interior
DOT	U.S. Department of Transportation
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
EP	Existing Plants
EPA	U.S. Environmental Protection Agency
ER	Enhanced Recovery
FE	Office of Fossil Energy
FEPs	Features, Events, and Processes
FERC	Federal Energy Regulatory Commission
FY	Fiscal Year
GES	Geological and Environmental Sciences
GHG	Greenhouse Gas
GIS	Geographic Information System
GWPC	Ground Water Protection Council

Acronym/Abbreviation	Definition
H_2	Hydrogen
H_2S	Hydrogen Sulfide
IEA	International Energy Agency
IEAGHG	IEA's Greenhouse Gas Programme
IGCC	Integrated Gasification Combined Cycle
IOGCC	Interstate Oil and Gas Compact Commission
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
MMt	Million Metric Tons
MVA	Monitoring, Verification, and Accounting
$MgCO_3$	Magnesium Carbonate
NACAP	North American Carbon Atlas Partnership
NARUC	National Association of Regulatory Utility Commissioners
NATCARB	National Carbon Sequestration Database and Geographic Information System
NETL	National Energy Technology Laboratory
NRAP	National Risk Assessment Partnership
OPPA	Office of Program Planning and Analyses
ORD	Office of Research and Development
OWG	Outreach Working Group
PCOR	Plains CO_2 Reduction Partnership
PNNL	Pacific Northwest National Laboratory
R&D	Research and Development
RCSP	Regional Carbon Sequestration Partnership
RUA	Regional University Alliance
STB	Surface Transportation Board
THMCB	Thermal, Hydrologic, Mechanical, Chemical, and Biological
UIC	Underground Injection Control
USDW	Underground Sources of Drinking Water
USGS	U.S. Geological Survey

I. Message to Stakeholders

Fossil fuels are considered the most dependable, cost-effective energy source in the world. The availability of these fuels to provide clean, affordable energy is essential for domestic and global prosperity and security well into the 21st century. However, a balance is needed between energy security and increasing concerns over the impacts due to increasing concentrations of greenhouse gases (GHGs) in the atmosphere – particularly carbon dioxide (CO_2). At present, roughly one-third of the CO_2 emissions in the United States come from power plants.

A combined portfolio of carbon management options can be implemented to manage current emission levels while enhancing energy security and building the technologies and knowledge base for export to other countries faced with reducing emissions. The U.S. portfolio includes: (1) use fuels with reduced carbon intensity – renewables, nuclear, and natural gas; (2) adopt more efficient technologies on both the energy demand and supply sides; and (3) use carbon capture and storage (CCS) technology. CCS is a viable emission management option because numerous studies have shown that it can account for up to 55 percent of the emissions mitigation needed to stabilize and ultimately reduce concentrations of CO_2.

The U.S. Department of Energy (DOE) launched its Carbon Sequestration Program in 1997. Consistent with Administration and Congressional priorities, CCS continues to be a key element of DOE's research and development (R&D) portfolio. Implemented by the National Energy Technology Laboratory (NETL) within DOE's Office of Fossil Energy (FE), the program is playing a lead role in CCS technology development and has made significant advances in the development of a broad range of effective and economically viable technologies. The Carbon Sequestration Technology Program Plan builds upon the recently published CCS RD&D Roadmap (http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CCSRoadmap.pdf) and provides additional details on specific research challenges and pathways that will need to be addressed through assessment and technology development. This publication also describes two complimentary DOE/NETL demonstration programs: the Clean Coal Power Initiative and Industrial Carbon Sequestration Program.

The overall objective of the Carbon Sequestration Program is to develop and advance CCS technologies that will be ready for widespread commercial deployment by 2020. To accomplish widespread deployment, four program goals have been established: (1) develop technologies that can separate, capture, transport, and store CO_2 using either direct or indirect systems that result in a less than 10 percent increase in the cost of energy by 2015; (2) develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ±30 percent by 2015; (3) develop technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zones by 2015; (4) complete Best Practices Manuals (BPMs) for site selection, characterization, site operations, and closure practices by 2020. Only by accomplishing these goals will CCS technologies be ready for safe, effective commercial deployment both domestically and abroad beginning in 2020 and through the next several decades.

The Carbon Sequestration Program directly supports the Interagency Task Force on CCS. The Interagency Task Force on CCS, comprised of 14 Executive Departments and Federal Agencies, delivered a series of recommendations to President Obama in August 2010 for overcoming the barriers to the widespread, cost-effective deployment of CCS within 10 years (http://www.fossil.energy.gov/programs/sequestration/ccstf/CCSTaskForceReport2010.pdf). The Task Force is co-chaired by DOE and the U.S. Environmental Protection Agency (EPA).

Since 1997, DOE's Carbon Sequestration Program has significantly advanced the CCS knowledge base in selected technology areas through a diverse portfolio of applied research projects. The portfolio includes cost-shared, industry-led, technology development projects; university research grants; collaborative work with other national laboratories; and research conducted in-house through NETL's Office of Research and Development (ORD). The Carbon Sequestration Program is comprised of three principal elements: Core R&D, Infrastructure, and Global Collaborations. It is the integration of these elements that will address technological and marketplace challenges, as described below:

Core R&D – The *Core R&D* element involves both applied laboratory- and pilot-scale research focused on developing new technologies and systems for GHG mitigation. *Core R&D* encompasses five technical focus areas for CCS technology and protocol development: (1) Pre-Combustion Capture; (2) Geologic Storage; (3) Monitoring, Verification, and Accounting (MVA); (4) Simulation and Risk Assessment; and (5) CO_2 Utilization. Included within Core R&D are American Recovery and Reinvestment Act of 2009 (ARRA) projects that focus on training graduate students in CCS-related activities.

Infrastructure – The *Infrastructure R&D* element involves confirmation of CO_2 storage approaches through activities such as the seven Regional Carbon Sequestration Partnerships (RCSPs), which are conducting field tests, engaging regional stakeholders, and characterizing opportunities for CO_2 storage in their regions. The seven RCSPs include representatives from more than 400 organizations, such as state agencies, national laboratories, universities, industry, and private companies, spanning 43 states and four Canadian provinces. The twenty (20) small-scale and nine (9) large-scale field projects implemented by the RCSPs involve site selection, CO_2 geologic injection into different geologic storage formation classes, monitoring, public outreach, and regulatory compliance. Other focus areas within the *Infrastructure R&D* element include other small- and large-scale projects, ARRA-funded technology transfer centers, and ARRA-funded site characterization projects that focus on characterizing geologic storage formations that offer opportunities for power plants and other industrial facilities to store large volumes of CO_2.

Global Collaborations –The United States views international engagement as an important component of our approach to responding to climate change. Accordingly, DOE is partnering with several international organizations, such as the International Energy Agency's Greenhouse Gas Programme (IEAGHG), the Carbon Sequestration Leadership Forum (CSLF), and the North American Carbon Atlas Partnership (NACAP). DOE is also directly engaged in a number of large-scale CCS demonstration projects around the world, spanning five continents.

Supporting technology R&D is one of the U.S. government's critical missions that can be leveraged to ensure a sustainable, secure, and affordable energy future. The U.S. government has a legitimate stake in the role of technology in protecting the environment and ensuring economic growth, prosperity, peace, and opportunity for its citizenry. DOE is one of the U.S. government's most technical cabinet agencies and technology development is one of the pillars upon which it was founded in 1977.

CCS and other clean coal technologies can play a critical role in mitigating CO_2 emissions while supporting energy security in the United States. DOE's Carbon Sequestration Program has positioned the United States on a path toward ensuring that the enabling technologies will be available to affect broad CCS deployment within a decade. Continued U.S. leadership in technology development and future deployment is important to the cultivation of economic rewards and new business opportunities both domestically and abroad.

II. Program Overview

Significant advances have been made in the development of CCS technologies since DOE launched the Carbon Sequestration Program. Managed within DOE's FE organization and implemented by NETL, the Carbon Sequestration Program works to develop effective and economically viable technology options for CCS. To accomplish this, the Carbon Sequestration Program focuses on developing technologies to capture, separate, compress, transport, and store CO_2 to reduce GHG emissions from the energy and other industries without adversely affecting the supply of energy or hindering economic growth. The Carbon Sequestration Program has the following major goals:

- Develop technologies that can separate, capture, transport, and store CO_2 using either direct or indirect systems that result in a less than 10 percent increase in the cost of energy at pre-combustion power plants by 2015.
- Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ±30 by 2015.
- Develop technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zones by 2015.
- Complete BPMs for site selection, characterization, site operations, and closure practices by 2020.

By 2020, the Carbon Sequestration Program will develop and advance CCS technologies that will be ready for widespread, commercial deployment. Reaching these goals will require working with several other applied R&D programs within FE that are developing and demonstrating technologies integral to fossil-fueled power generation with carbon capture.

The individual components of the program are managed collectively by the Carbon Sequestration Program and a complementary NETL program – the Existing Plants (EP) Program. The Carbon Sequestration Program now focuses on geologic storage and its associated monitoring, verification, and accounting (MVA), as well as pre-combustion CO_2 emissions control for integrated gasification combined cycle (IGCC) power plants. In Fiscal Year (FY) 2008, the EP Program initiated a research portfolio that includes both post- and oxy-combustion CO_2 emissions control technology for existing coal-fired power plants and related CO_2 compression, which focuses on applying carbon capture to existing and new pulverized coal plants. Additional internal research assistance and support for the Carbon Sequestration Program is provided by NETL's ORD.

A. Program Structure

DOE's Carbon Sequestration Program is comprised of three principal elements: *Core R&D, Infrastructure, and Global Collaborations*. The relationship among the elements is shown in Figure 2-1. *Core R&D* is driven by the technology needs determined by industry and others and divides the challenges into focus areas. The *Infrastructure* element includes the RCSPs and other large-volume field tests where validation of various CCS technology options and their efficacy are being confirmed. The Carbon Sequestration Program also participates in testing at large-volume tests through *Global Collaborations*.

The *Global Collaborations* and *Infrastructure* elements test new technologies and benefit from specific solutions developed in the *Core R&D* element. In turn, data gaps and lessons learned from large-scale demonstrations are fed back to the *Core R&D* element to guide future R&D, as well as international demonstration projects and RCSP field projects.

The Carbon Sequestration Program also supports the development of best practices for CCS that will benefit projects implementing CCS at a commercial scale, such as in the Clean Coal Power Initiative (CCPI) and Industrial Carbon Sequestration Programs. In general, DOE-applied research is being leveraged with field tests to assess the technical and economic viability of CCS as a GHG mitigation option. DOE has established the following plan to ensure that the goal of developing these technologies is met:

- Manage Core R&D activities within specific focus areas where each identifies separate research pathways to develop essential technologies.

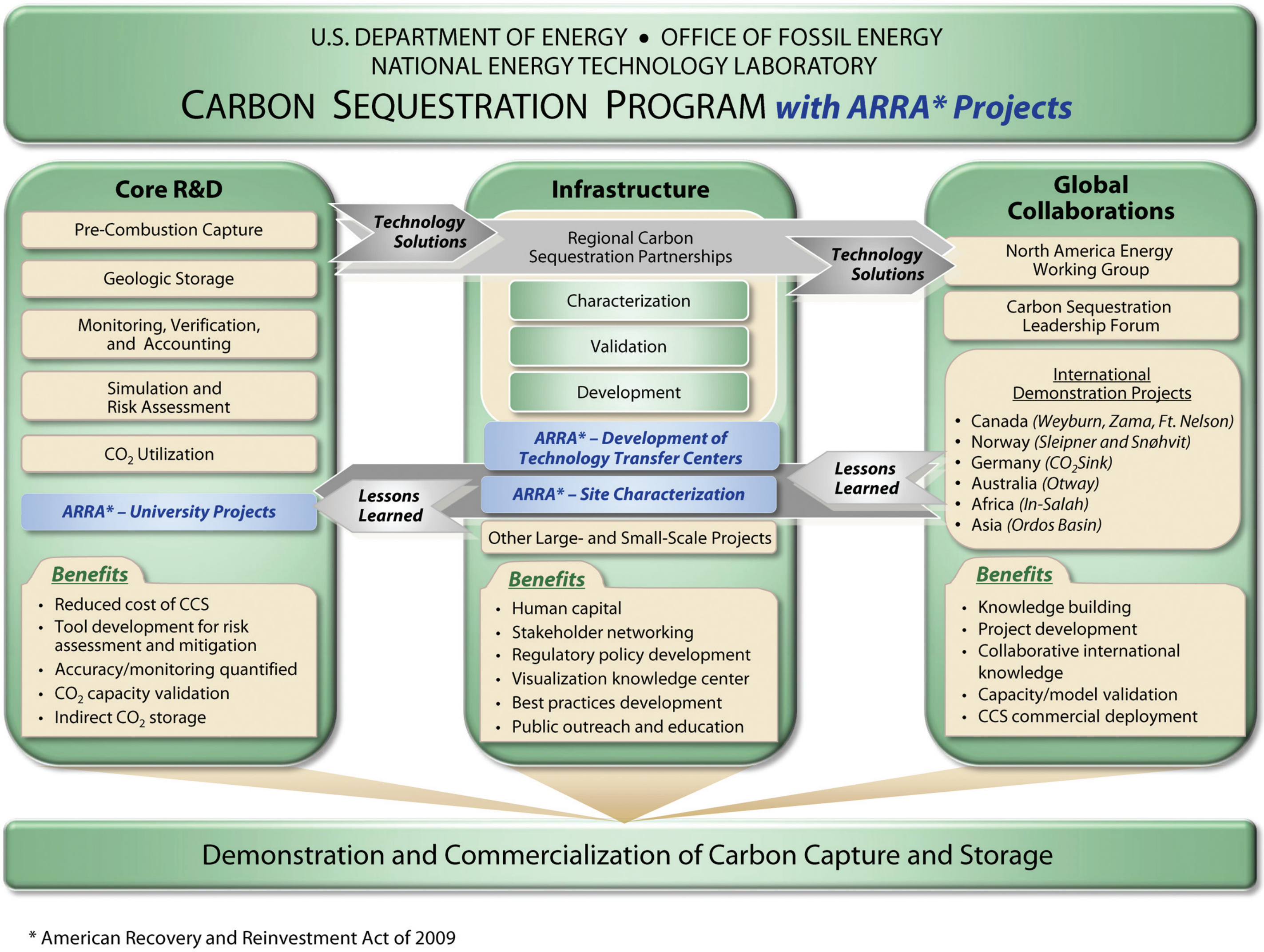


Figure 2-1. Carbon Sequestration Program Structure with ARRA Activities

- Utilize the RCSP Initiative to develop future infrastructure, as well as validate and field test technologies through all stages leading to commercialization.
- Collaborate with global partnerships and leadership forums by providing technology solutions and receiving test results from global initiatives and international demonstration projects.
- Engage a wide variety of industry; Federal, state, and local government agencies; academia; and environmental organizations.
- Work with NETL's Office of Program Planning and Analyses (OPPA) to determine the benefits of research and establish a systems approach to confirm that technologies are capable of meeting Carbon Sequestration Program goals.

B. Program Funding

DOE's Carbon Sequestration Program budget has significantly increased over the last decade in response to U.S. efforts to reduce anthropogenic CO_2 emissions. The total program budget has increased from approximately $10 million in 2000 to $154 million in 2010 (Figure 2-2). The increase in the program budget reflects the high capital expenditures associated with the Validation and Development Phase injection tests of the RCSP Initiative.

The RCSP Initiative accounts for approximately half of the program funding, with the remaining allotted to R&D that is being conducted in collaboration with industry, states, private research institutions, and academia (Figure 2-3).

Among the challenges for wide-scale deployment of CCS technologies after 2020 is the need to identify appropriate CO_2 storage locations throughout the United States, develop a transmission system, and have a pool of trained professionals and trades people

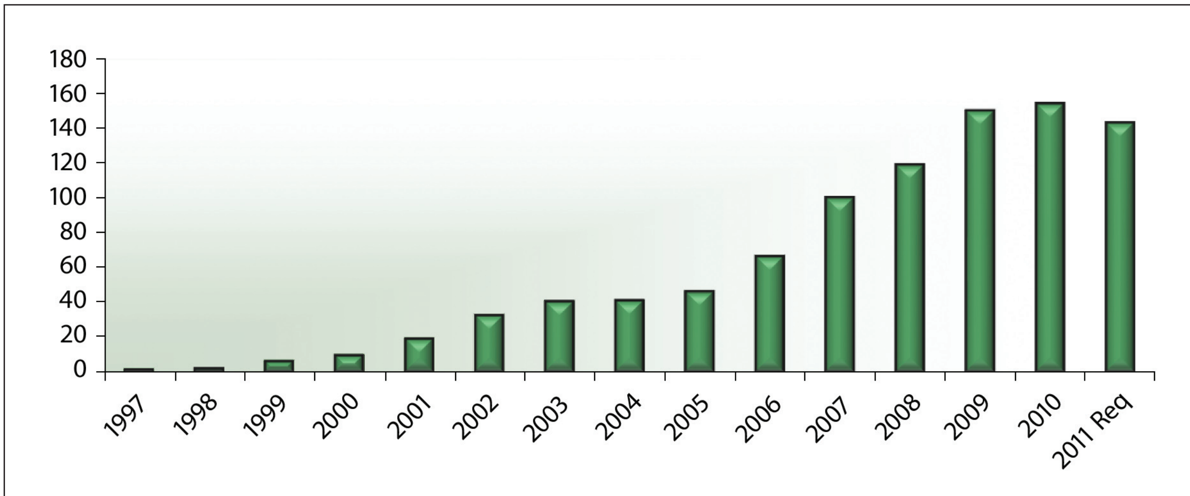


Figure 2-2. Carbon Sequestration Program Budgets from FY1997-2011

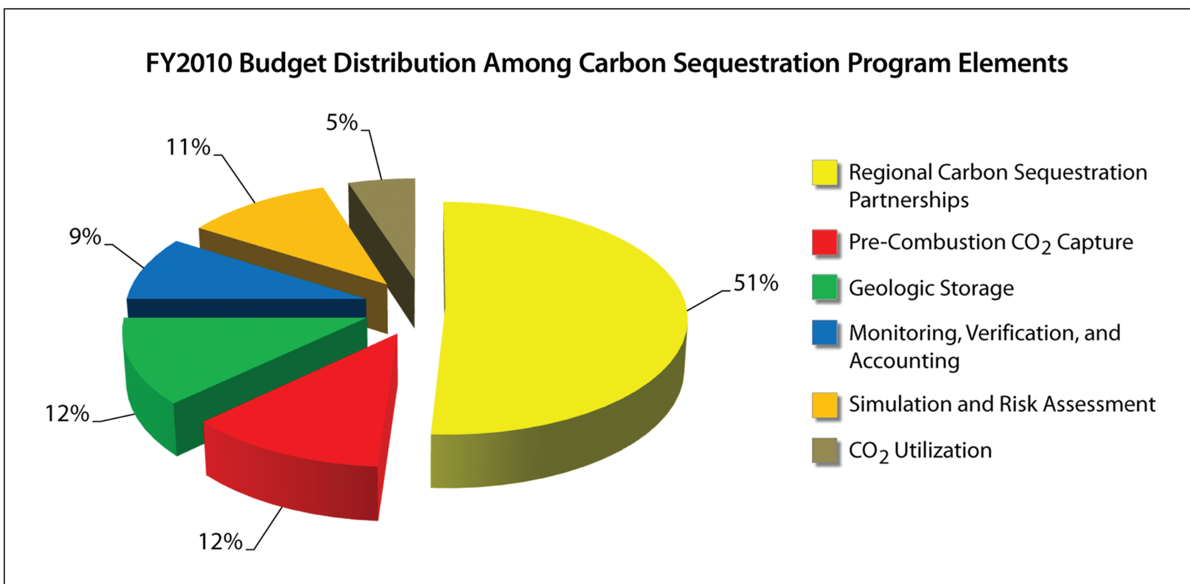


Figure 2-3. FY2010 Budget Distribution Among Carbon Sequestration Program Elements

to build and operate these facilities. ARRA funding is helping to address these program challenges through the following efforts (http://www.netl.doe.gov/technologies/carbon_seq/arra/index.html):

- **Geologic Sequestration Site Characterization** - Accelerate the comprehensive identification and characterization of large-volume geologic formations, thus augmenting characterization efforts and refinement of geologic storage resource potential conducted by the RCSPs. Ten projects were awarded at the end of 2009 to assess high priority sites for future commercial interests.

- **Geologic Sequestration Training and Research** - Develop the next generation of scientists and engineers for CCS by implementing training and research efforts conducted primarily at colleges and universities. Fifty projects were awarded, including seven CCS training centers and 43 grants to universities to support students pursuing R&D and future careers with CCS.

C. Programmatic Successes

This Carbon Sequestration Program Plan describes the plan that will guide the program in 2011 and beyond. Over the last decade, the program has had many successes in all three program elements. More details on programmatic successes can be found in the DOE/NETL publication titled, "Carbon Sequestration FY2008-2009 Accomplishments," published in November 2010 (available at: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CS_AR2008-2009.pdf).

III. Core R&D

The first of the three Carbon Sequestration Program elements, the Core R&D Element, focuses on developing new CCS technologies to the point of pre-commercial demonstration. The Core element includes five technical focus areas: (1) Pre-Combustion Capture; (2) Geologic Storage; (3) Monitoring, Verification, and Accounting (MVA); (4) Simulation and Risk Assessment; and (5) CO_2 Utilization – each with specific research goals applicable to each focus area (Figure 3-1).

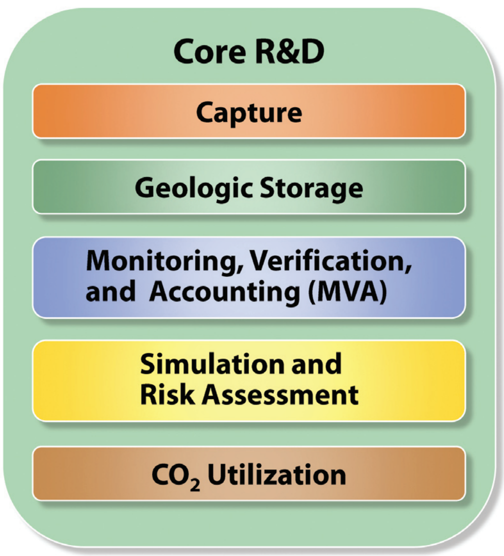


Figure 3-1. Core R&D Focus Areas

Within each focus area, specific challenges or uncertainties have been identified and research pathways were then constructed to address these challenges. The level of technology R&D conducted by the program ranges from laboratory- to pilot-scale activities.

Technologies are normally developed in the Core R&D element to the point where individual companies, utilities, and other business entities are able to design, manufacture, and build the equipment and instrumentation needed to implement or commercialize the processes. The Core R&D element is implemented through cost-shared cooperative agreements and grants with industry and academic institutions, field work research at other national laboratory complexes, and research at NETL's ORD.

A. Pre-Combustion Capture Focus Area

Background

Carbon dioxide capture is defined as the separation of CO_2 from emissions sources or within the process. For large, point sources, there are three capture configurations – pre-combustion capture, post-combustion capture, and oxy-combustion capture. As previously noted, research on post-combustion and oxy-combustion is carried out within the EP Program. The Carbon Sequestration Program focuses on developing technologies used to reduce the cost of capture and separation for pre-combustion systems.

Pre-combustion capture is mainly applicable to IGCC power plants and refers to removal of the CO_2 from the synthesis gas (syngas) prior to its combustion for power production. A simplified process schematic for pre-combustion CO_2 capture is shown below (Figure 3-2).

Near-term applications of CO_2 capture from pre-combustion systems will likely involve improvements to the existing state of the art physical or chemical absorption processes currently being used by industry.

Pre-Combustion Capture Research Goals

Current state of the art pre-combustion technologies would raise the cost of electricity by approximately 30 percent.[1] The Carbon Sequestration Program goal is to identify technologies that can reduce the cost of pre-combustion capture to no more than 10 percent by 2015. The program would then support projects to test the most promising technologies at pilot scale through 2018, as summarized in Table 3-1.

DOE's system analyses have shown that the current portfolio of technologies have demonstrated progress toward meeting the cost targets at bench scale. Integrating the existing portfolio of technologies with other advanced IGCC system improvements has

[1] Current and Future Technologies for Gasification Based Power Generation, Volume 2 Carbon Capture, Revision 1.

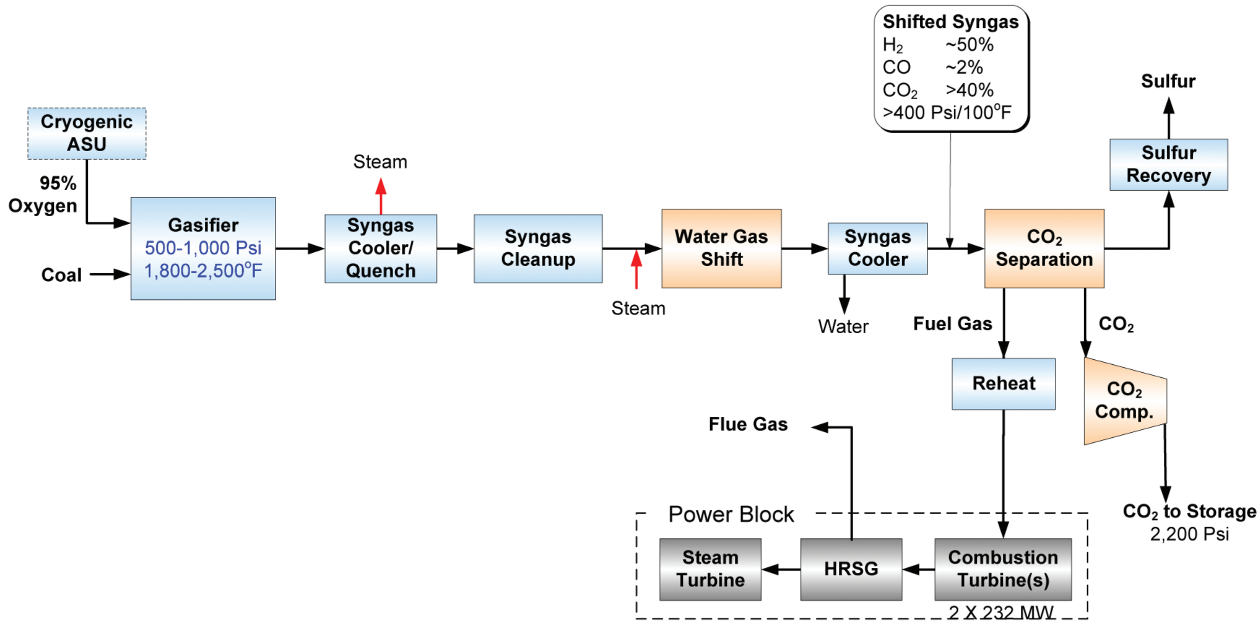


Figure 3-2. Schematic for Pre-Combustion CO_2 Capture

reduced the cost of pre-combustion capture from 30 percent to 16 percent. Continued support of these and other technology efforts will keep DOE on track to have appropriate technologies that meet its goal. It is anticipated that these technologies will be ready by 2015 for small-scale pilot testing to begin addressing issues with scaleup and integration.

Table 3-1. Pre-Combustion Capture Goals and Proposed Timeline

2015	Develop a comprehensive portfolio of bench-scale technologies which, if combined with other system advances, will enable new power production technology with CO_2 capture (e.g., IGCC) to produce electricity at a cost of no more than 10 percent above the reference power plant without CO_2 capture.
2015	Begin testing pre-combustion promising technologies at 0.1-MW scale.
2018	Initiate the development of second generation pre-combustion technologies which, if combined, will enable production with IGCC facilities at near-zero additional cost.

Pre-Combustion Capture Technologies

The Carbon Sequestration Program is focusing on mid- and long-term technology solutions that offer opportunities to dramatically reduce the costs associated with pre-combustion capture. The program is currently funding the development of several advanced pre-combustion CO_2 capture technologies that have the potential to provide step-change improvements in both cost and performance as compared to the physical solvent-based Selexol™ and Rectisol® processes. Three technologies areas show significant promise and could be integrated into IGCC systems, including:

- Physical Solvents
- Solid Sorbents
- Membranes, *which could also be integrated with advanced solvents*

Each technology approach has a specific application, advantages over others, and challenges that are the focus of the existing and future research. The issues for each of the technologies being supported are summarized in Table 3-2.

Table 3-2. Pre-Combustion Capture Technologies

Pre-Combustion CO_2 Capture Technology Objective	Application	Advantages	Research Focus
Physical Solvent	• Solvents with higher CO_2 adsorption capacity and regenerated at higher pressure. • Solvent readily dissolves CO_2. Solubility is directly proportional to CO_2 partial pressure and inversely proportional to temperature, making physical solvents more applicable to low temperature, high-pressure applications (cooled syngas). • Regeneration normally occurs by pressure swing. • Existing solvents, such as Selexol, are operational at scale, but are not cost effective.	• CO_2 recovery does not require heat to reverse a chemical reaction. • Common for same solvent to have high hydrogen sulfide (H_2S) solubility, allowing for combined CO_2/H_2S removal. • System concepts in which CO_2 is recovered with some steam stripping rather than flashed, and delivered at a higher pressure, may optimize processes for power systems.	• Increase solvent loading capacity to reduce energy demand and capital costs. • Increase temperature and pressure operating window for solvent to reduce energy demand and compression requirements. • Reduce impacts of co-contaminants and temperature on solvent degradation. • Increase CO_2 selectivity.
Solid Sorbent	• Sorbents with higher CO_2 adsorption capacity and regenerated at higher pressure. • When sorbent pellets are contacted with syngas, CO_2 is physically adsorbed onto sites and/or dissolves into the pore structure of the solid. Rate and capacity are directly proportional to CO_2 partial pressure, making these sorbents more applicable to high pressure applications. Regeneration normally occurs by pressure swing.	• CO_2 recovery does not require heat to reverse a reaction. • Common for H_2S to also have high solubility in the same sorbent, meaning CO_2 and H_2S capture can be combined. • System concepts in which CO_2 is recovered with some steam stripping rather than flashed, and delivered at a higher pressure may optimize processes for power systems.	• Address pressure drop of CO_2 during flash recovery. • Reduce energy requirements needed to cool synthesis gas for CO_2 capture and heating and re-humidify for firing to turbine. • Increase recovery of hydrogen (H_2) during CO_2 capture.

Table 3-2. Pre-Combustion Capture Technologies (cont'd)

Pre-Combustion CO_2 Capture Technology Objective	Application	Advantages	Research Focus
Membrane	• A membrane material which selectively allows H_2 or CO_2 to permeate, used in gasification operations with concentrated streams of H_2 and CO_2. • Membranes capable of operating at higher temperature and pressure. Eliminate cooling and reheating of gas streams and produce CO_2 at higher pressure than conventional technology. • In a solvent hybrid system, the synthesis gas is contacted with a membrane, and a solvent on the permeate side absorbs CO_2 and creates a partial pressure differential to draw CO_2 across the membrane.	• Reduce energy penalty since no steam load is required. • CO_2 delivered at high pressure. • Can drive CO shift reaction toward completion, reducing costs. • In liquid solvent hybrids, the membrane shields the amine from the contaminants in synthesis gas, reducing attrition and allowing higher loading differentials between lean and rich amine.	• Develop novel material to reduce costs of materials and manufacturing. • Examine impacts of co-contaminants, temperature, and pressure on membranes and solvents. • Improve selectivity to increase purity of CO_2. • Improve permeability to decrease pressure drop.

B. Geologic Storage Focus Area

Background

Geologic CO_2 storage involves the injection of supercritical CO_2 into deep geologic formations (injection zones) overlain by competent sealing formations and geologic traps that will prevent the CO_2 from escaping. Current research and field studies are focused on developing better understanding of the science and technologies for five storage types: clastic formations; carbonate formations; deep, unmineable coal seams; organic-rich shales; and basalt interflow zones.

Geologic storage of oil, gas, and CO_2 in the deep subsurface has been naturally occurring for millions of years. For more than 40 years the oil industry has injected CO_2 in depleted oil reservoirs for the recovery of additional product through enhanced oil recovery (EOR). Natural analogs to CO_2 storage exist throughout the United States, where CO_2 has been naturally trapped in geologic confined layers and structures deep below the surface of the Earth. Lessons learned from natural systems, EOR operations, gas storage, and sponsored CO_2 storage projects are all important for developing storage technologies for a future CCS industry. The following figure illustrates the geologic storage concept and the different areas of research being pursued within the Geologic Storage Focus Area (Figure 3-3).

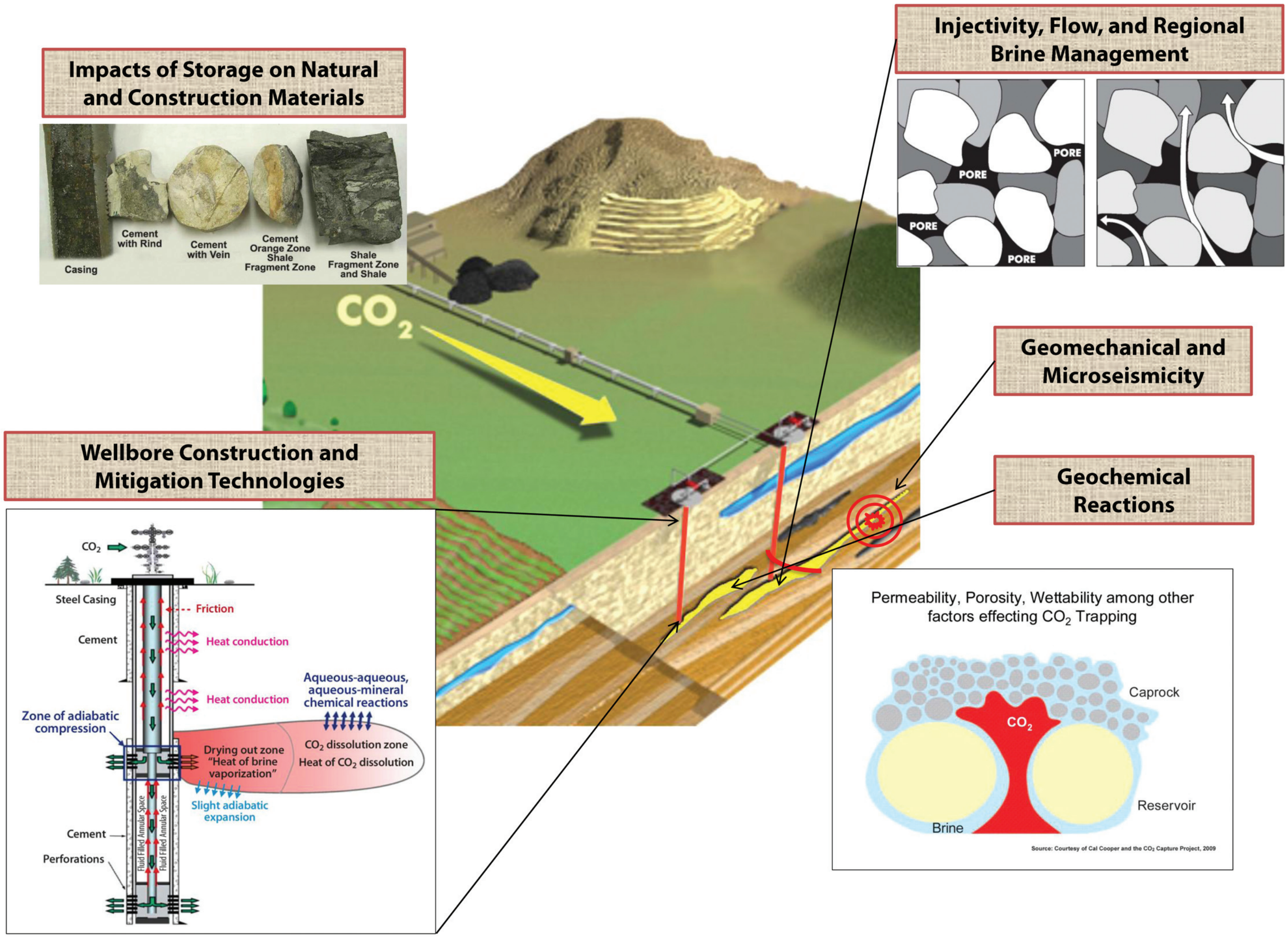


Figure 3-3. Diagram of Geologic Storage Concept Highlighting Current Research Areas

Geological Storage Research Goals

Geologic systems are capable of storing CO_2 and hydrocarbons for millions of years. These natural systems offer analogs that can be used to help develop strategies to improve our understanding of processes and develop technologies to improve our understanding of injectivity, storage resource potential, and future capacity and effectiveness of different storage formations and their associated geologic storage formation classification. DOE is supporting the development of tools and protocols to improve the ability to predict future capacity in closed and open geologic systems within $\pm$30 percent, assess and minimize the impacts of CO_2 and co-contaminants on geophysical processes, and develop remediation technologies that will prevent or reduce possible releases through existing wellbores and natural pathways. The following table shows Geologic Storage Focus Area goals that will need to be achieved in order for the Carbon Sequestration Program to meet its programmatic goals (Table 3-3). Achieving these individual goals will help enable technologies and protocols to be available to the commercial CCS industry by 2020.

Table 3-3. Geologic Storage Research Goals and Proposed Timeline

2015	Demonstrate enhanced CO_2 trapping and storage capacity at pre-commercial scale, and demonstrate the ability to predict CO_2 storage capacity with ±30 percent accuracy.
2016	Assess impacts of co-contaminants on CO_2 storage activities.
2018	Validate storage capacity ±30 percent within a key storage reservoir system.
2020	Demonstrate remediation technologies for natural release pathways and existing wells.

Geologic Science and Technologies Research

A future geologic CO_2 storage industry will need to augment existing technologies with novel technologies to ensure permanent storage of CO_2.

The Carbon Sequestration Program looks to support research that will better our scientific understanding, including:

- Wellbore Technologies
- Remediation Technologies
- Fluid Flow
- Pressure and Brine Management
- Geomechanical and Geochemical Processes

The program is also looking to support research to develop technologies that can improve containment, improve injection operations, increase reservoir storage efficiency, and mitigate releases. The following table summarizes how the program's research is addressing the critical geologic storage scientific and technology barriers (Table 3-4).

Table 3-4. Geologic Storage Science/Technologies

CO_2 Storage Science/ Technology Objective	Application	Research Focus
Wellbore Technologies	Properly constructed wellbores are necessary to ensure safe and reliable injection operations and long-term containment. Wellbores must be made of materials that are resistant to the materials being injected, any changes in the fluid chemistry of the injection formations, mechanical stresses on the storage formation and seals, and have good cement bonds within the geologic formation to ensure containment. Drilling and stimulation technologies are also an important area of consideration. These technologies may be advantageous for CO_2 storage projects by enhancing capacity and injectivity.	• Improve construction materials for products, such as casing, linings, and cements, which are resistant to CO_2 and other co-contaminants and the fluids in the reservoir which may react with the CO_2. • Adapt tools that allow improved directional drilling and stimulation methods to increase the use of marginal storage reservoirs. • Improve protocols and technologies, which increase injectivity, improve storage efficiency, and increase capacity.
Mitigation Technologies	Permanent CO_2 storage relies on the presence of a competent geologic seal which will retain the CO_2 for millennia. Penetrations, such as wellbores, and natural faults and fractures all offer potential release pathways for CO_2 to migrate to the surface or Underground Sources of Drinking Water (USDW), and negate the benefits of removing the CO_2 from the atmosphere. Mitigation technologies are necessary to ensure that any possible releases through these pathways can be addressed. Some mitigation technologies and protocols in the oil and gas industry exist today that can be used to permanently seal wells that are poorly constructed or have degraded after years of operation. These existing technologies will need to be adopted and new technologies will need to be developed to mitigate potential CO_2 release.	• Develop techniques and technologies to mitigate poor cement bonds behind well casing by squeezing fluids (i.e., cement) to improve the seal between the formation and well. • Develop micro drilling and injection technologies to access release pathways and inject fluids to reduce flow. • Develop biological or chemical additives that could seal release pathways at the caprock or wellbore, but have no impact on injectivity and capacity efficiency in the storage formation.

Table 3-4. Geologic Storage Science/Technologies (cont'd)

CO_2 Storage Science/ Technology Objective	Application	Research Focus
Fluid Flow, Pressure, and Brine Management	Carbon dioxide injected into the subsurface will need to move through the storage formation between the grains of sand in clastic formations, vugs or fractures in carbonate reservoirs, and cleats in coalbeds. The CO_2 typically will take the path of least resistance which may result in pore space not being fully utilized (poor sweep efficiency). Carbon dioxide will displace brine during injection operations. In open systems, the brine will typically move laterally. In closed systems, brine may need to be removed to ensure that pressure does not impede the injection operations. In either case, brine management techniques will need to be understood since both situations could impact CCS operations.	• Support research to better understand fluid flow in different geologic strata that may help improve operation and design requirements and improve injectivity and sweep efficiency. • Understand the impacts of injection on both closed and open systems both at the project and basin scales. • Support the development of technologies and protocols for the management of brine extracted from CCS operations. • Determine the optimal placement of injection and monitoring wells in each type of depositional environment. • Understand the effects of multiple injection wells and effects of pressure, regional CO_2, and groundwater flow.
Geochemical Impacts	Carbon dioxide will react with rock interface, minerals, and brines in the storage formation. Chemical processes relevant to subsurface CO_2 storage include aqueous speciation, dissolution/precipitation, microbial-mediated redox reactions, ion-exchange between solutions and minerals, and surface chemical reactions occurring at phase interfaces. All of these reactions will have impacts on the physical processes happening in the storage formation, the caprock, and at a smaller scale through leakage pathways.	• Understand the impacts of CO_2 on mineralization rates in different formation types to improve CCS operations and storage integrity. • Understand potential impacts of co-containments on precipitation of minerals and their effect on the storage formation. • Understand the impacts of geochemical reactions with brine, cements, casing materials, and materials that seal faults and fractures.
Geomechanical Impacts	Injection of CO_2 will occur at pressures above the natural reservoir pressure. In most projects the injection pressure will be below the fracture pressure for the caprock, significantly reducing the risk of release and associated geomechanical effects. Some injection operations may also take place in hydraulic fractured (stimulated) wells that were used for hydrocarbon recovery. All of these situations lead to questions about the impacts of CO_2 injection on the reservoir and confining formations.	• Use microseismicity to understand reservoir characteristics and fluid flow. • Examine impacts on caprock, faults, fractures, and existing wellbore materials. • Understand the general pressure distribution on different reservoirs based on their depositional environment. • Determine impacts of injection on existing hydraulically featured geology.

C. Monitoring, Verification, and Accounting (MVA) Focus Area

Background

An MVA program is designed to confirm permanent storage of CO_2 in geologic formations through monitoring capabilities that are both reliable and cost effective. Monitoring is an important aspect of CO_2 injection, since it focuses on a number of permanence issues. Monitoring technologies can be developed for surface, near-surface, and subsurface applications to ensure that injection and abandoned wells are structurally sound and that CO_2 will remain within the injection formation. Should Federal or state GHG accounting regulations and/or CO_2 emissions reductions be required, monitoring can be used to account for the quantity of CO_2 that has been injected and stored underground. The location of the injected CO_2 plume in the underground formation can also be determined, via monitoring, to satisfy operating requirements under EPA's Underground Injection Control (UIC) Program and ensure that potable groundwater and ecosystems are protected.

Figure 3-4 displays the various monitoring tools that could be employed to monitor the fate of the CO_2 within a geologic system (subsurface, near-surface, and surface). Data analyzed through acquisition of information from these tools could also be used to optimize injection operations, sweep efficiency, and identify release pathways.

MVA Research Goals

It will be necessary to improve existing monitoring technologies, development of novel systems, and protocols to satisfy regulations to track the fate of subsurface CO_2 and quantify any emissions from reservoirs. The Carbon Sequestration Program is sponsoring the development of technologies and protocols by 2020 that are broadly applicable in different geologic storage classes and have sufficient accuracy to account for greater than 99 percent of all injected CO_2. If necessary, the tools will support project developers to help quantify emissions from CCS projects in the unlikely event that CO_2 migrates out of the injection zone. Finally, coupled with our increased understanding of these

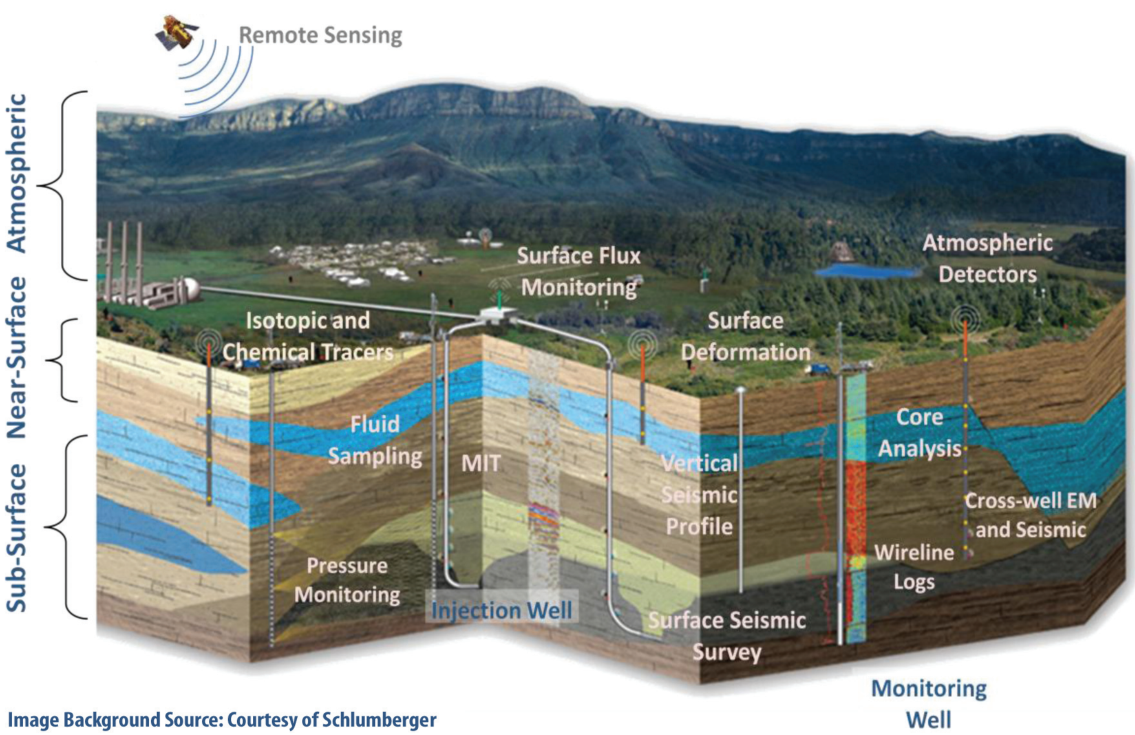


Figure 3-4. MVA Tools Utilized Throughout a Geologic System

systems and reservoir models, MVA tools will help in the development of one of DOE's goals to quantify storage capacity within ±30 percent accuracy. The MVA research goals defined in Table 3-5 provide a roadmap for research technologies that will allow the Carbon Sequestration Program to meet its programmatic goals.

Table 3-5. MVA Goals and Proposed Timeline

2011	Develop the first edition of the MVA BPM, identify gaps in technologies, and award the first of a series of advanced MVA projects.
2012	Complete the development of prototype technologies and protocols, which demonstrate that greater than or equal to 95 percent of the CO_2 can be accounted for within a reservoir for commercial-scale storage with current and advanced technologies.
2015	Complete the development of prototype technologies and protocols which demonstrate that greater than or equal to 99 percent of the CO_2 can be accounted for within a reservoir for commercial-scale storage with current and advanced technologies.
2020	Complete the final edition of the MVA BPM, which will provide the commercial CCS industry with guidelines for technology selection and protocols for safe, effective geologic CO_2 storage.

MVA Technologies

The tools and protocols that provide assurance of storage permanence for geologic CO_2 storage are the primary benefit of MVA research. Research conducted in this focus area includes developing and integrating:

- Atmospheric Monitoring Technologies
- Remote Sensing and Near-Surface Monitoring Technologies
- Subsurface Monitoring Technologies
- Design of Intelligent Monitoring Networks and Monitoring Protocols

These research areas, in conjunction with small- and large-scale injection projects, are expected to produce MVA tools that can be applied in a systematic approach to address target formation(s) depth(s), porosities, permeabilities, temperature(s), pressure(s), and associated confining formation properties for each project. An additional benefit of research efforts will be the reduction in cost of these tools. Finally, the increased capabilities of MVA tools will yield the ability to account for the location of injected CO_2 and any potential release, thereby meeting not only the project storage goals, but also ensuring the protection of human health and the environment.

A summary of the key MVA technologies, their applications, and associated research focus is contained in Table 3-6.

Table 3-6. MVA Technologies

MVA Objective	Application	Research Focus
Atmospheric Monitoring Technologies	Testing at the surface and in the atmosphere to identify and quantify possible releases from storage projects is critical to the success of future CCS projects. It is unlikely that CO_2 will reach the atmosphere, but in the event it does, technologies will be necessary to monitor and quantify releases of CO_2 from wellbores, faults, and diffuse soil releases.	• Research the development and application of novel chemical and isotopic tracers which may be precursors to CO_2 release at the surface. • Develop systems to monitor flux from soils to determine changes from baselines to identify release and quantify releases. • Research open path systems and CO_2 detectors to identify releases from injected CO_2.
Remote Sensing and Near-Surface Monitoring Technologies	Detecting near-surface releases in the vadose zone and groundwater sources are important to protecting USDW. It is also important to be able to detect pooling of high concentrations of CO_2 in low lying areas and in structures. The benefits of monitoring in this zone are that natural variations of CO_2 in the soil are typically minimal since biological activity typically occurs closer to the surface.	• Utilize remote sensing platforms to detect gas concentrations, land surface deformations, and biological impacts as indicators of CO_2 release and fate of CO_2 in the subsurface. • Advance water quality and soil gas analysis for isotopes, tracers, and organic and inorganic carbon as advanced warning signs of release. • Advance geophysical methods needed to image CO_2 or sense changes in geochemistry in the vadose zone.
Subsurface Monitoring Technologies	To be able to achieve 99 percent storage permanence, monitoring tools must be able to locate CO_2 in the target and surrounding storage formations. Carbon dioxide will migrate through the target formation through paths of least resistance. It is important to understand the fate of the injected CO_2 to help identify possible releases as well as inform future monitoring events and simulation models. Carbon dioxide measurement is relatively easy near the injection well, but it becomes more challenging and expensive to perform these measurements over a large area typical of a geologic storage project. Technologies developed should be able to sense small changes from background levels.	• Advance geophysical methods and protocols to image CO_2 or sense changes in geochemistry in the target or surrounding formations. • Develop remote sensing techniques that monitor parameters, such as land surface deformation, to correlate CO_2 movement in the deep subsurface. • Improve sensors for subsurface monitoring of pressure and temperature, which can withstand long-term exposure to temp and pressure. • Improve tools and interpretation of data from well logging and seismic surveys which can increase the resolution of existing technologies and assess integrity of wellbores. • Develop novel tracers and sampling tools and methodologies for deep geologic sampling to use as indicators of CO_2 transport in the target formations.
Design of Intelligent Monitoring Networks and Monitoring Protocols	A number of monitoring tools may be deployed during various phases of the storage project. Project developers will need to develop systems and protocols for deploying different technologies to address events that arise during a storage project. Certain technologies are low cost, but can serve as indicators of release, while others may only be deployed after an event has been identified. Research is needed to develop these intelligent systems that would inform project developers of the capabilities of different MVA technologies and when to apply each.	• Research and quantify the capabilities of different technologies to monitor and measure CO_2 in the subsurface. • Research and design monitoring networks to indicate CO_2 release, confirm release, and quantify release to support mitigation efforts and GHG reporting requirements.

D. Simulation and Risk Assessment Focus Area

Background

In CCS projects, simulation models are critical for predicting several scenarios related to the target geologic formation. Results from the simulation models will be incorporated into risk assessments on a project-by-project basis and will also include basin-scale developments. For example, as CCS becomes deployed in major basins, macro model results will be needed to manage reservoirs for pressure management, plume migration, and potential risks of multiple CO_2 injection projects across the basin.

Specifically, simulation models can also be used to predict the thermal impacts and hydrologic flow of CO_2 in the target formation; geochemical and thermal changes that may occur in the reservoir; geomechanical effects on the target formation, seals, and release pathways, such as faults, fractures, and wellbores; and the effect of biological responses in the presence of supercritical CO_2.

Risk assessment (or more formally, risk analysis), which tailors the development of effective risk assessment protocols and models to individual CO_2 storage sites, is often performed at the early stages of a project to help in site selection, communicating project goals and procedures to the public, and aiding regulators in permitting for the project. Risk assessment is also necessary in identifying potential site problems and developing mitigation procedures so that immediate action can be implemented should a problem arise. Risk assessment processes include both project implementation risks, operational risks, and long-term storage risks over millennia. Quantifying risks is necessary to support site selection, inform projects developers as they design MVA protocols and well designs, and determine risks. Calculation of risk profiles is a common approach to assessing the predicted performance of large-scale projects. These also determine which risks and curves will need to be tracked during the lifecycle of the project to support project design, optimize operations, and quantification of long-term project costs and potential liabilities that support decisions on decommissioning and long-term stewardship. The environmental risk for geologic CO_2 storage projects increases and then plateaus during injection. Once injection has ceased, environmental risk begins to decrease over time, as shown in Figure 3-5.

Goals for Simulation and Risk Assessment

As CCS capacity increases and projects become commercial beyond 2020, the importance of accurate geologic models and robust risk assessment protocols will become increasingly important to project developers, regulators, and other stakeholders. A major goal of the

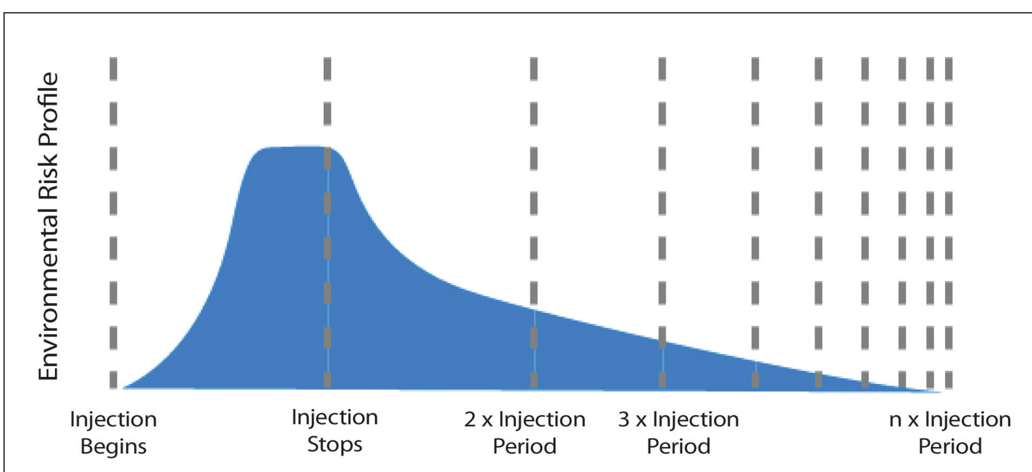


Figure 3-5. Schematic Risk Profile for a CO_2 Storage Project (Benson, 2007; WRI presentation)

program is to continue improvements to the models and risk assessment protocols. Specific goals within the Simulation and Risk Assessment Focus Area that will enable the Carbon Sequestration Program to meet current programmatic goals are shown in Table 3-7.

Table 3-7. Simulation and Risk Assessment Goals and Proposed Timeline

2015	Validate and improve existing simulation codes which will enhance the prediction and accuracy of CO_2 movement in deep geologic formations to within ±30 percent accuracy.
2020	Validate risk assessment process models using results from large-scale storage projects to develop risk assessment profiles for specific projects.
2025	Develop basin-scale models to support the management of pressure, CO_2 plume, and saline plume impacts from multiple injections for long-term stewardship in major basins of the United States.

Simulation and Risk Assessment Technologies

Simulation is a critical step in the systematic development of a monitoring program for a geologic CO_2 storage project because the selection of an appropriate measurement method and/or instrument is based on whether the method or instrument can provide the data necessary to address a particular technical question. Effective monitoring can confirm that the project is performing as expected from predictive models. The linkage between model results and monitoring data can be complicated if monitoring programs are not designed to address which parameters should be monitored, including timing of measurements, location, spatial scale, and resolution of measurements, to match with model parameters. This is particularly valuable in the early stages of a project when the opportunity exists to alter the project to ensure long-term storage and improve efficiency. Monitoring data collected early in a project are often used to refine and calibrate the predictive model, improving the basis for predicting the longer-term performance of the project.

Simulations are utilized to predict the following:

- Temporal and spatial migration of the injected CO_2 plume
- Effect(s) of geochemical reactions on CO_2 trapping and long-term porosity and permeability
- Caprock and wellbore integrity; the impact of thermal/compositional gradients in the reservoir
- Pathways of CO_2 out of the reservoir
- Importance of secondary barriers
- Effect(s) of unplanned hydraulic fracturing
- Extent of upward migration of CO_2 along the outside of the well casing
- Impacts of cement dissolution
- Consequences of wellbore failure

A significant amount of work has been completed to develop simulators for CO_2 developed by industry and academia that couple Thermal, Hydrologic, Mechanical, Chemical, and Biological (THMCB) impacts of CO_2 injection. Several different models (independent and coupled) are currently being used in many field projects to validate laboratory observations. Current research in this focus area includes refinement and coupling of models that can represent these processes for this focus area:

- Thermal and Hydrologic Modeling
- Geochemical Effects of CO_2 Injection
- Geomechanical Effects of CO_2 Injection
- Biologic Modeling
- Rick Assessment Identification and Quantification

A summary of simulation and risk assessment technologies, their description and application, as well as their research focus is contained in Table 3-8.

Table 3-8. Simulation and Risk Assessment Technologies

Simulation and Risk Assessment Objective	Application	Research Focus
Thermal and Hydrologic Modeling	A number of two- and three-dimensional numerical codes for simulating coupled groundwater and heat flow exist today that are capable of modeling CO_2 flow though porous and fractured media. These models are critical to predicting the performance and informing the project developer of risk and operational design of CCS projects.	• Improve limited research focus of existing models to improve coupling of these processes. • Improve regional hydrologic modeling of flow for basin-scale CCS operations accounting for depositional conditions.
Geochemical Effects of CO_2 injection	Chemical modeling for CCS can take several forms, and ideally should include processes such as aqueous speciation, dissolution/precipitation, redox processes, ion-exchange between solutions and minerals, and surface chemical reactions occurring at phase interfaces.	• Improve reaction kinetics. • Examine effects on porosity and permeability. • Examine effects on geomechanical processes. • Research coupling with transport and multiphase flow and reaction.
Geomechanical Effects of CO_2 Injection	Geomechanical processes include effects of fluid pressure, elastic and non-recoverable deformation, fracturing and larger-scale faulting. Simulation algorithms have shown extremely rapid advances over the past two decades, including very sophisticated gridding techniques and mathematical optimization methods.	• Improve coupling of hydrologic and mechanical models for impacts on faults, fractures, and wellbores. • Examine the impact of regional pressure increases on basin-scale seismicity. • Examine the scaling of pore-scale models to predict project and regional impacts of mechanical process that might impact hydrologic flow and risks.
Biologic Modeling	The influence that microorganisms have in the subsurface underscores the importance of understanding how CO_2 storage will affect microbial activity, a topic of great uncertainty. This information may be used to prevent or mitigate negative consequences associated with CO_2 injection. Furthermore, understanding CO_2 reservoir microbiology may offer opportunities to enhance CO_2 retention.	• Assess the impacts to microbial communities. • Examine the effects on permeability to reduce risks of release.
Risk Assessment Identification and Quantification	Risk assessment is the systematic identification of features, events, or processes (FEPs) which might pose a potential risk to the operations or impacts from a CCS project. Understanding these risks is critical to the design, optimization, permitting, and implementation of CCS projects. In addition to identification of potential "pathways" for migration, equally important is the identification of specific consequences. For geologic storage, some consequences of concern that have been identified in laboratory studies include brine contamination of USDWs, unintended migration of CO_2 into petroleum resources or other infringement on mineral rights, and long-term CO_2 seepage into the atmosphere. Building upon field operation experience and simulation modeling will support the development of rigorous risk assessment modeling for CCS.	• Develop standard processes for risk assessment. • Develop risk assessment databases for FEPs to predict risk and impacts in different types of geologic formations. • Compare the predictive methods against observations to demonstrate reliability and accuracy as well as to reduce uncertainties. • Integrate risk assessment with simulation, operation design, and monitoring activities to optimize performance.

E. CO_2 Utilization Focus Area

Background

Although permanent CO_2 storage in geologic formations looks promising as an option for reducing CO_2 emissions, this approach may not be viable for all CO_2 emitters and could result in no economic benefit at significant cost. Therefore, it is highly desirable to develop alternatives that can use captured CO_2 or convert it to a useful product, such as a fuel, chemical, or plastic, with revenue from the CO_2 use offsetting a portion of the CO_2 capture cost. Although using CO_2 has some potential to reduce GHG emissions to the atmosphere, as discussed below, CO_2 has certain disadvantages as a chemical reactant. Many existing industrial processes emit unused CO_2 to the atmosphere. Therefore, a careful analysis is required to ensure that a proposed CO_2 utilization scheme actually reduces net CO_2 emissions.

Carbon dioxide is far down the energy scale and is, therefore, rather inert and non-reactive. In fact, this inertness is the reason for some of the uses identified for beneficial use. Each potential use of CO_2 has an energy requirement, and an analysis is required to ensure that

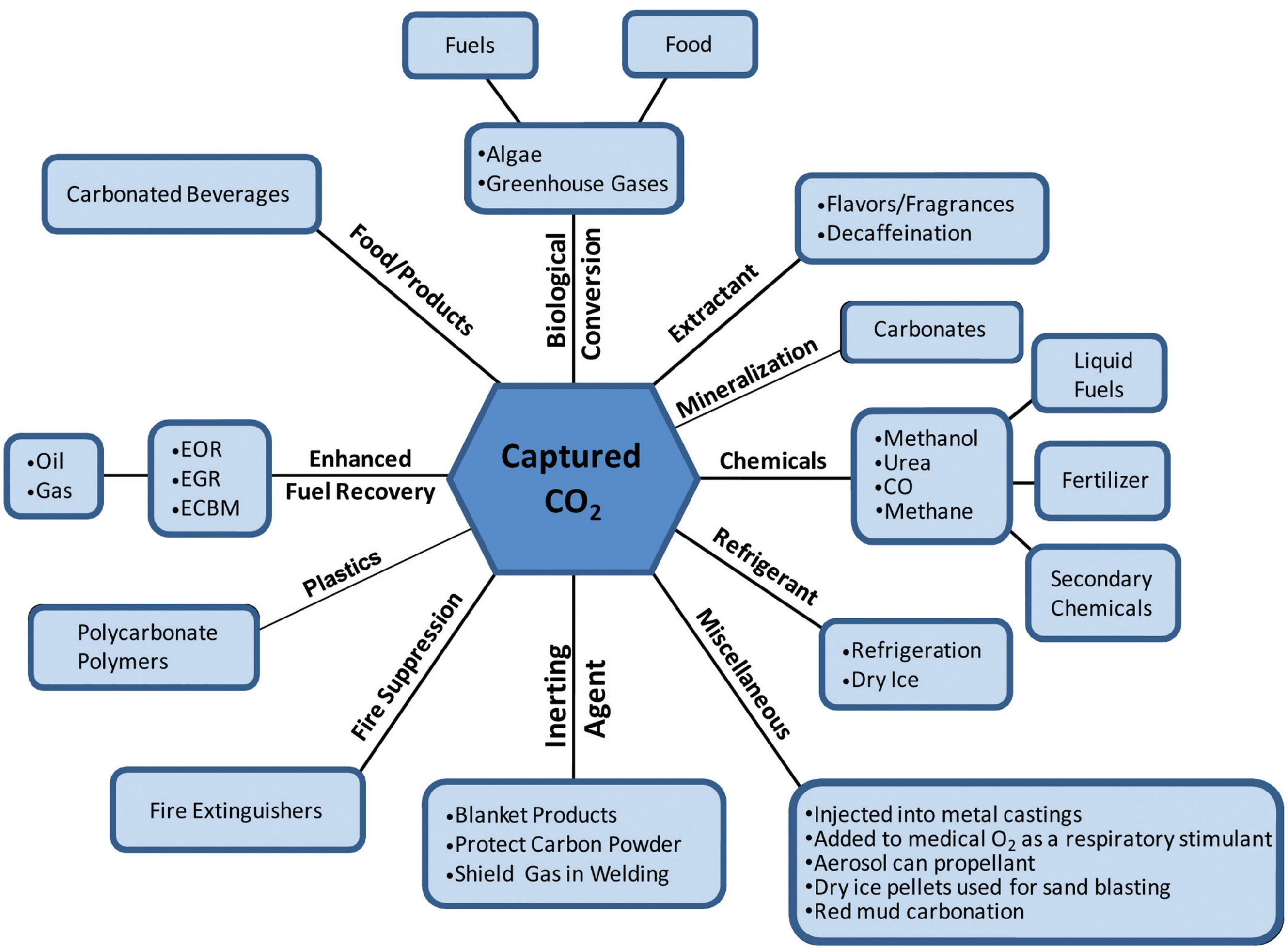


Figure 3-6. Schematic Illustrating the Uses of CO_2

more CO_2 is used rather than emitted in producing the required energy.

Figure 3-6 illustrates most of the current and potential uses of CO_2. However, many of these are small and typically emit the CO_2 to the atmosphere after use and, thus, do not result in any net reduction in CO_2 emissions. Some of the more significant current and potential uses of CO_2 are highlighted in the research underway in this focus area.

CO_2 Utilization Goals

The CO_2 Utilization Focus Area covers a broad area of research with different technical challenges. The goals of the Carbon Sequestration Program are set to achieve successful implementation of various applications at different time horizons and include the goals described in Table 3-9.

Table 3-9. CO_2 Utilization Goals and Proposed Timeline

2015	Develop technologies for fixing CO_2 in stable products with indirect sequestration at costs of no more than $10 per metric ton of CO_2 used.
2016	Test the most promising technologies at pilot scale for chemical or mineral conversion of CO_2 into useful products.
2020	Develop technologies for fixing CO_2 in stable products at costs near zero for each metric ton of CO_2 mitigated.

In general, the area of CO_2 utilization for carbon storage is relatively new and less well-known compared to other storage approaches, such as geologic storage. Thus, more exploratory technological investigations are needed to discover new applications and new reactions. Many challenges exist for achieving successful CO_2 utilization and some of them are discussed below. A summary of CO_2 utilization objectives, their description and application, as well as research focus is shown in Table 3-10.

Table 3-10. CO_2 Utilization Technologies

CO_2 Utilization Focus	Description	Research Focus
Cement	Instead of the traditional energy intensive steam curing technology, develop a concrete curing process that consumes substantial amounts of waste CO_2 from onsite flue gases and local combustion sources. The produced concrete products should exhibit material performance equal to that of the traditional curing process, while using less energy. This use of CO_2 should fix the carbon for many years. The transition between demonstration and commercial scale should be rapid, since the new process and technology is anticipated to require limited modification to the existing curing process.	• Improve curing rates and CO_2 yield to increase efficiency of CO_2 use. • Develop curing processes based on carbonation chemistry rather than hydration chemistry to reduce energy requirements and CO_2 emissions. • Develop cement to meet American Standard Test Method (ASTM) standards.
Polycarbonate Plastics	Traditional monomers, such as ethylene and propylene, can be combined with CO_2 to produce polycarbonates, such as polyethylene carbonate and polypropylene carbonate. The advantage of this process is that it copolymerizes CO_2 directly with other monomers without having to first convert the CO_2 to CO or some other reactive species, thus significantly reducing energy requirements. There are many potential uses for polycarbonate plastics, including coatings, plastic bags, and laminates. Depending on the final fate of the plastic, such as a landfill, this use could represent semi-permanent storage of carbon. This promising CO_2 utilization technology needs to be proven at pilot scale.	• Utilize waste energy or alternative energy sources to convert CO_2. • Develop catalysts to reduce energy requirements. • Develop stabilizers to inhibit degradation of plastics.
Mineralization	Carbonate mineralization refers to the conversion of CO_2 to solid inorganic carbonates. Naturally occurring alkaline and alkaline-earth oxides react chemically with CO_2 to produce minerals, such as calcium carbonate ($CaCO_3$) and magnesium carbonate (MgCO3). These minerals are highly stable and can be used in construction or disposed of without concern that the CO_2 they contain will release into the atmosphere. One problem is that these reactions tend to be slow, and unless the reactions are carried out in situ, there is a large weight of rocks to move. Carbonates can also be used as filler materials in paper and plastic products.	• Reduce energy requirements for grinding feedstock materials. • Utilize waste streams from existing mining operations. • Develop chemicals or catalysts to speed reaction rates and reduce thermal and pressure requirements. • Meet industrial standards for building materials.
Enhanced Hydrocarbon Recovery	Enhanced Recovery (ER) involves the injection of CO_2 into a depleted oil or gas bearing field to increase production. This could involve injecting CO_2 into clastic, carbonate, coal, or organic shale formations.	• Maximize the amount of CO_2 that could be stored as well as hydrocarbons produced as part of these ER operations.

IV. Infrastructure R&D

The second element of DOE's Carbon Sequestration Program is Infrastructure R&D for geologic storage. DOE determined early in the program's development that regionally addressing CO_2 mitigation would be the most effective way to address differences in geology, climate, population density, infrastructure (human capital), and socioeconomic development throughout the United States. To support the development of regional infrastructure for CCS throughout the United States, this element consists of several efforts, including:

- Development of small- and large-scale CO_2 injection tests in different classes of geologic formations, which include the efforts of the RCSPs and other field projects.

- Development of geologic storage BPMs to communicate lessons learned from field projects to industry, regulators, and the public.

- National efforts to characterize storage formations and reduce uncertainty associated with capacity resource estimates.

- Support the development of human capital, stakeholder networking, regulatory policy development, carbon mitigation plans, and public outreach and education throughout the United States.

A. Regional Carbon Sequestration Partnerships

The RCSP Initiative established the foundation that is being further enhanced by additional small- and large-scale projects, addressing specific applied research for injectivity, capacity verification, and safe geologic storage progressing toward commercialization of the technology. In 2003, DOE awarded cooperative agreements to seven RCSPs, shown in Figure 4-1, through an open and competitive solicitation. The

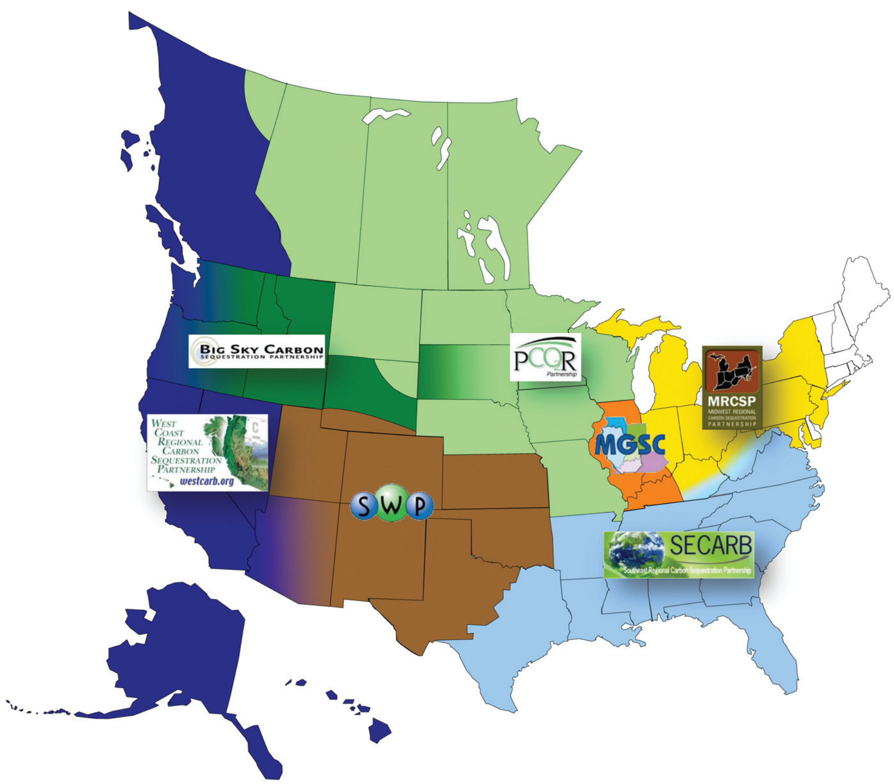


Figure 4-1. Regional Carbon Sequestration Partnership Regions

seven RCSPs focused on the CCS opportunities within their specific regions, while collectively building an effective and robust nationwide initiative. Through this process each RCSP has developed a regional carbon management plan to identify the most suitable storage strategies and technologies, aid in regulatory development, and propose appropriate infrastructure for CCS commercialization within their respective regions.

The RCSPs are public/private partnerships comprised of more than 400 organizations covering 43 states and four Canadian provinces. The partners include representatives from state and local agencies, regional universities, national laboratories, non-government organizations, foreign government agencies, engineering and research firms, electric utilities, oil and gas companies, and other industrial partners. Each of the RCSPs are led by one organization that manages the RCSP activities, including the characterization efforts, planning and leading the small- and large-scale injection tests, and integrating the results. Lead organizations for each RCSP are identified in Table 4-1.

The RCSP Initiative is being implemented in three phases:

- Characterization Phase (2003-2005): Initial characterization of their region's potential to store CO_2 in different geologic formations.
- Validation Phase (2005-2011): Validation of the most promising regional storage opportunities through a series of small-scale field tests.
- Development Phase (2008-2018+): Implementation of large-scale field testing involving at least 1 million metric tons of CO_2 per project to confirm that CO_2 injection and storage can be achieved safely, permanently, and economically.

In addition to the RCSP efforts to implement small- and large-scale field projects, the RCSPs are also working to develop human capital, encourage stakeholder networking, support regulatory policy development, develop carbon mitigation plans, and enhance public outreach and education throughout the United States.

Table 4-1. Regional Carbon Sequestration Partnerships

RCSP	Acronym/Abbreviated Name	Lead Organization
Big Sky Carbon Sequestration Partnership	BSCSP	Montana State University
Midwest Geological Sequestration Consortium	MGSC	Illinois State Geological Survey
Midwest Regional Carbon Sequestration Partnership	MRCSP	Battelle Memorial Institute
Plains CO_2 Reduction Partnership	PCOR	University of North Dakota Energy and Environmental Research Center
Southeast Regional Carbon Sequestration Partnership	SECARB	Southern States Energy Board
Southwest Regional Partnership on Carbon Sequestration	SWP	New Mexico Institute of Mining and Technology
West Coast Regional Carbon Sequestration Partnership	WESTCARB	California Energy Commission

Validation Phase Pilot-Scale (Small-Scale) Projects

The purpose of small-scale characterization and injection projects is to explore and validate various depositional systems throughout basins within the United States and the capability to inject into clastic and carbonate depositional formations, coal seams, and basalts, and validate regional seals to contain injected CO_2. These small-scale projects validate that CO_2 storage resources are available in the target formations throughout the region, as well as validate their potential injection rates through injectivity testing (Figure 4-2). The information gathered during these tests provides valuable information regarding storage formation typically not explored for other reasons and will inform future characterization and storage resource estimates under development by DOE and the U.S. Geological Survey (USGS). The Carbon Sequestration Program strategy includes an established set of field test objectives applicable to all of the small-scale injection projects:

- Confirm storage resources and injectivity estimates established for target reservoirs.
- Validate the effectiveness of simulation models and MVA technologies to predict and measure CO_2 movement in the geologic formations and confirm the integrity of the seals.
- Develop guidelines for well completion, operations, and abandonment in order to maximize CO_2 storage potential and mitigate release.
- Develop public outreach plans and communicate the benefits of CCS to various stakeholders.
- Satisfy the regulatory permitting requirements for small-scale CCS projects.
- Gather information to improve estimates for storage capacity that could be used to update regional and national storage resource and capacity estimates.

Small-scale projects that address these objectives could support new technologies that would be further developed and tested during large-scale injection projects to further demonstrate the capability for geologic storage.

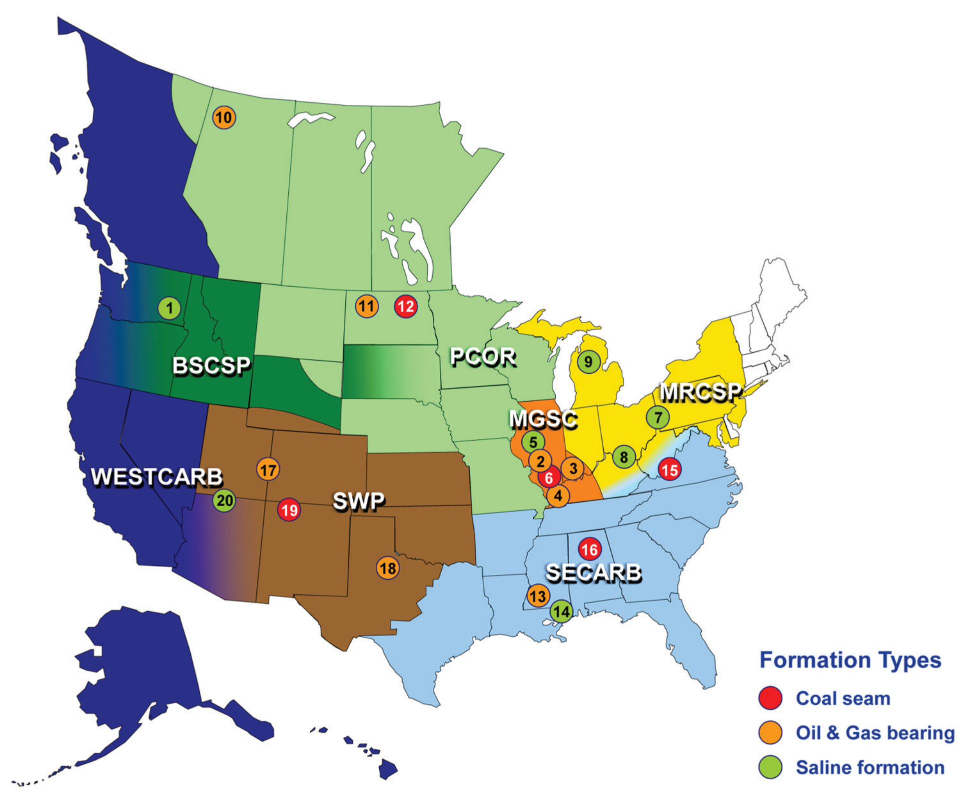


Figure 4-2. Validation Phase Geologic CO_2 Storage Projects

Development Phase (Large-Scale) CO_2 Injection Projects

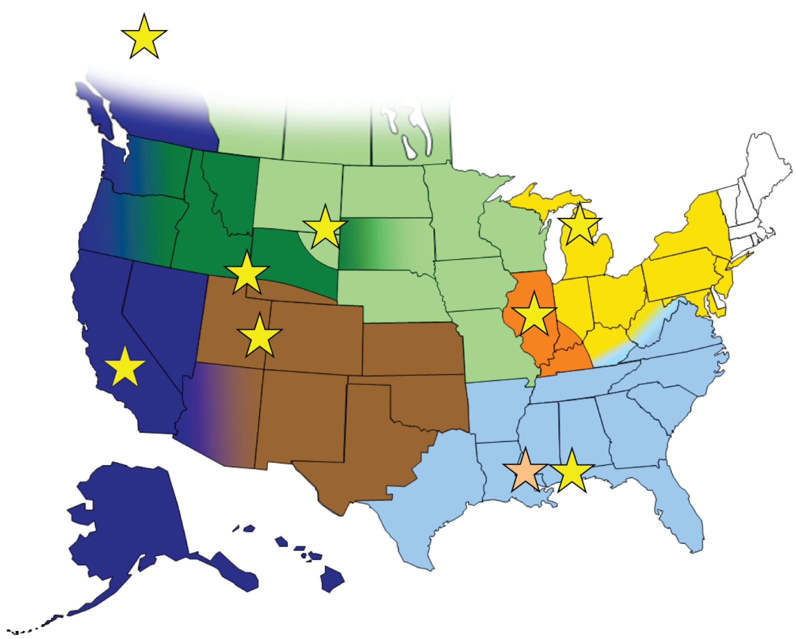
Large-scale field tests in different geological storage classes must be conducted to confirm that CO_2 capture, transportation, injection, and storage can be achieved safely, permanently, and economically. Results from these tests will provide a more thorough understanding of migration and permanent storage of CO_2 within various open and closed depositional systems. The storage types and formations being tested are considered regionally significant and are expected to have the potential to store hundreds of years of CO_2 stationary source emissions.

Specifically, large-scale field tests will address practical issues, such as sustainable injectivity, well design for both integrity and storage resource utilization, and reservoir behavior, with respect to prolonged injection (Figure 4-3). Complete assessments of these issues are necessary to validate and improve model predictions concerning the behavior of injected CO_2 at scale; establish the engineering and scientific processes for successfully implementing and validating long-term, safe storage of carbon; and achieve cost-effective integration with power plants and other large emission sources for carbon capture.

The large-scale field projects are implemented in three stages and typically require at least eight years to implement. These three stages include the site characterization, operations, and closure phases. Activities conducted throughout each of these stages are further described in Figure 4-4.

In order to validate that CCS can be conducted at commercial scale; a number of key goals are being pursued by each of the large-scale projects:

- Prove adequate injectivity and available capacity at near-commercial scale by injecting CO_2 over an extended period of time at rates at least 10 percent of commercial-scale projects.



Injection Ongoing
Injection Scheduled 2011–2015

* Note: Information current as of June 2010.
Some locations presented on map may differ from final injection location.

Figure 4-3. Development Phase Geologic CO_2 Storage Projects

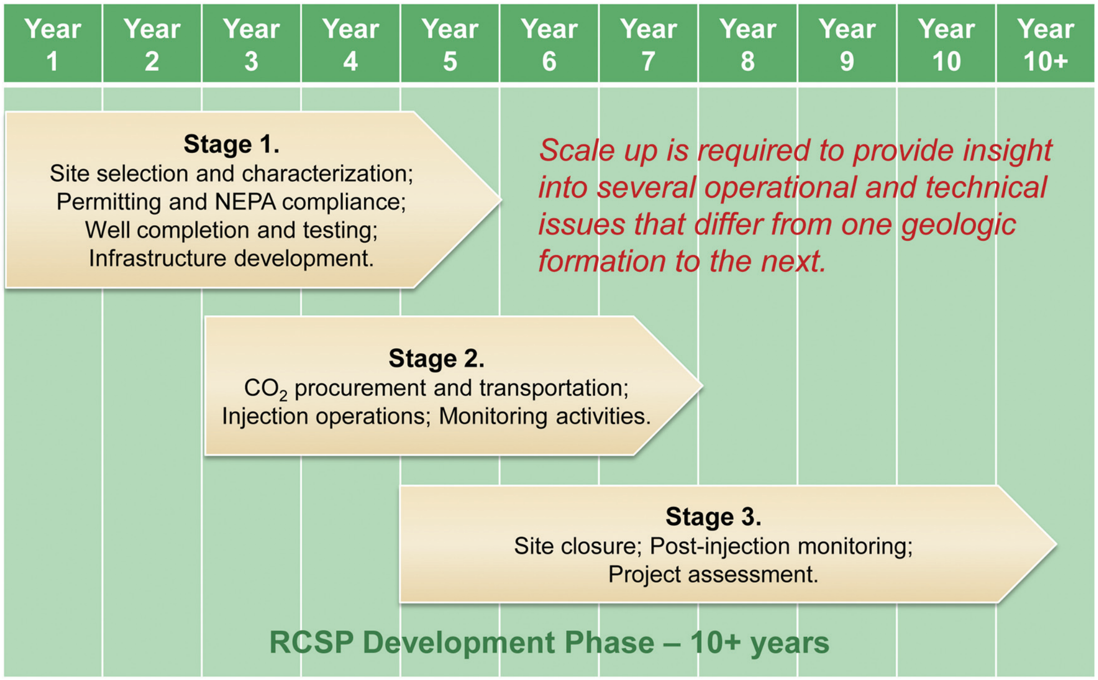


Figure 4-4. Approximate Timeline for Large-Scale CO_2 Injection Tests

- Prove storage permanence by validating that CO_2 will be contained in the target formations; develop technologies and protocols to quantify potential releases and that the projects do not adversely impact USDWs and/or cause CO_2 to be released to the atmosphere.

- Determine the areal extent of the CO_2 plume and potential release pathways by monitoring the areal extent and vertical migration of the CO_2 during and after project completion and develop methodologies to determine the presence/absence of release pathways such that the proposed mitigation strategy can sustain a near-zero release.

- Develop risk assessment strategies by indentifying risk parameters, probability and potential impact of occurrence, and mitigation strategies.

- Integrate results with other large-scale projects through the RCSP technical working groups to develop BPMs for geologic storage projects.

- Engage in public outreach and education about CCS and participate in the Outreach Working Group (OWG).

- Engage in the development of an effective regulatory and legal framework for the safe, long-term injection and geologic CO_2 storage in the regions that the projects are developed.

Results obtained from these efforts will provide the foundation for validating that CCS technologies can be commercially deployed throughout the United States. These large-scale projects will be necessary to validate storage projects integrated with carbon capture technologies from various CO_2 sources and geologic storage in all storage types in multiple basins throughout the United States.

Impact of Geologic Storage Formation Classes on CCS Opportunities in the United States

A significant part of DOE's program goals involves identifying geologic formations that can store large volumes of CO_2, receive CO_2 at an efficient and economic rate of injection, and safely retain the CO_2 over long time periods.

The effectiveness of CO_2 injection and storage operations and the ability of technologies to monitor and simulate CO_2 storage will differ among geologic formation classes. Additional work is needed to understand how chemical composition, geomechanical properties, compartmentalization, heterogeneity, seismicity, and reservoir architecture impact CO_2 storage and other impurities. There are 11 different classes of geologic storage formations (deltaic, shelf clastic, shelf carbonate, strandplain, reef, fluvial deltaic, eolian, fluvial and alluvial, turbidite, coal, and basalt) and two different classes of seals (shale and evaporites) that need to be considered when developing future field projects.

Evaluation of the geology and depositional environments through laboratory testing and small- and large-scale field projects is critical across these storage formation classes and seals to validate that the geology of the United States is available for large-scale development. Efforts like the RCSPs and other small- and large-scale field tests are critical to enhancing our knowledge and understanding of which systems will be available for CCS deployment in the future. The table below provides a summary of DOE-supported field projects that are assessing the different geologic storage classes (Table 4-2). This information will be used to identify future research efforts to better understand storage in these different geologic storage formation classes.

National Geologic Carbon Storage Characterization Efforts

The efforts of the RCSPs and other large- and small-scale projects have substantially increased the knowledge base about the potential to use different formations not previously explored for oil and gas as

Table 4-2. DOE's Efforts to Test CO_2 Storage Formation Classes (2010)

Matrix of Field Activities in Different Geologic Formation Classes											
Field Activities	**High Potential Formations**					**Medium Potential Formations**				**Lower or Unknown Potential Formations**	
	Deltaic	Shelf Clastic	Shelf Carbonate	Strandplain	Reef	Fluvial Deltaic	Eolian	Fluvial & Aluvial	Turbidite	Coal	Basalt (LIP)
Large-scale Field Tests	–	1	–	–	1	3	–	1	–	–	–
Small-scale Field Tests	3	2	4	1	2	–	–	2	–	5	1
Site Characterization	1	–	8	6	–	3	3	2	2	–	1

Notes:
The number in the cell is the number of investigations by NETL per geologic storage formation classification.
Large-scale Field Tests – Injection of more than 1,000,000 tons of CO_2.
Small-scale Field Tests – Injection of less than 500,000 tons of CO_2 for EOR and 100,000 tons for saline formations.
Site Characterization – Characterize the subsurface at a location with the potential to inject at least 30,000,000 tons of CO_2.
Reservoir potentials were inferred from petroleum industry data and field data from the Carbon Sequestration Program.
Known depositional environments have been determined by initial site characterization.

storage reservoirs for CO_2. Yet, there is a lack of existing information on storage formations throughout the United States that will require a considerable effort by research organizations, state geologic surveys, and industry to gather existing data and collect new information. This will help to reduce the uncertainty associated with CO_2 storage resource estimates, improve our understanding of storage efficiency, and better understand injectivity rates and the performance and extent of regional seals needed to contain the CO_2. Activities like increased well drilling, long 2-D seismic lines, and digitization of older exploration records are needed to increase the information available on these high priority geologic basins and storage formations.

Current estimates for CO_2 storage resources are not restricted by economic or social constraints. Future efforts will begin to consider how commercial facilities will need to operate and the minimum reservoir conditions and demographic requirements needed to develop commercial projects. In addition, CO_2 storage resources will continue to be further refined as future storage projects systematically move through a project maturation process as defined in DOE's BPM for Site Screening, Site Selection, and Initial Characterization,[2] published in January 2011 (Figure 4-5). These efforts will provide considerably improved data and methodologies for determining national estimates, as well as specific estimates for projects developed in different parts of the basins.

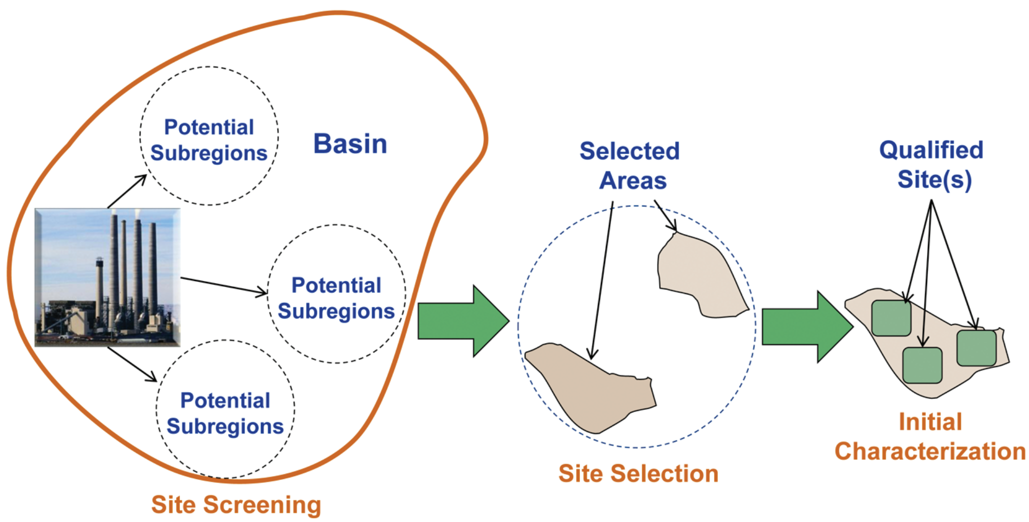


Figure 4-5. Graphical Representation of "Project Site Maturation" Through the Exploration Phase

2 U.S. Department of Energy National Energy Technology Laboratory, "Site Screening, Site Selection, and Initial Characterization for Storage of CO_2 in Deep Geologic Formations," DOE/NETL-401/090808, http://www.netl.doe.gov/technologies/carbon_seq/refshelf/BPM-SiteScreening.pdf.

ARRA Efforts to Promote Infrastructure Development

The ARRA provided funding for two efforts that complement the existing Carbon Sequestration Program's efforts to develop CCS infrastructure in the United States. The efforts include the establishment of seven CCS training centers and 10 geologic site characterization projects throughout the United States.

The seven CCS training centers were provided $1 million each through 2012 to support the development of professional training classes and academic curricula for scientists, engineers, lawyers, business persons, and others involved in CCS project development (http://www.netl.doe.gov/technologies/carbon_seq/arra/training.html). In addition, the training centers will provide instruction on science and the process of planning and operating commercial CCS projects. The goal of these training centers is to become self sustaining and continue the training efforts without Federal funding to ensure that a future CCS workforce will be technically capable when CCS is commercially deployed.

The 10 site characterization projects were awarded nearly $100 million to characterize high priority geologic storage formations that have the potential for future commercial-scale storage projects (http://www.netl.doe.gov/technologies/carbon_seq/arra/characterization.html). These site characterization efforts include drilling stratigraphic wells to collect whole and side-wall core data on confining and injection zones, conducting comprehensive logging suites and formation evaluation tests, and analyzing the chemistry of formation rocks and fluids. The characterization efforts will also include the acquisition of 2-D and/or 3-D seismic surveys that integrate rock property data acquired from new wellbores with other existing data to validate seismic responses. The integration of this data will provide a better understanding of the subsurface properties that will be necessary to develop dynamic models to account for CO_2 migration. All of the information gathered from these projects will be incorporated into the National Carbon Sequestration Database and Geographic Information System (NATCARB) to improve future CO_2 storage resource estimates in the United States. These efforts represent a small step towards understanding the geology of potential storage formations in the United States.

Best Practice Manuals (BPMs) and Working Groups – Technology Transfer

DOE promotes information sharing among the RCSPs through the various technical working groups established by DOE/NETL. These groups include experts from each of the seven RCSPs whose objective is to provide a forum for sharing information and developing uniform approaches for contending with common challenges. The working groups are titled: (1) Geological and Infrastructure; (2) MVA; (3) Simulation and Risk Assessment; (4) Capture and Transportation; (5) GIS and Database; (6) Water; and (7) Public Outreach and Education.

The working groups also address the need to develop a uniform approach to address a variety of common issues including an organized, national perspective on characterization, validation, and development issues for DOE's Carbon Sequestration Program. These working groups remain active and are integral to the successful progress of the RCSPs through the Development Phase and the planned field activities.

The lessons learned throughout these tests are being integrated into a series of BPMs on topics such as MVA, site selection and characterization, simulation and risk assessment, understanding impacts of geologic storage classes, well construction and closure, public outreach and education, and terrestrial storage. The first edition of the BPMs will be completed by early 2011 and updated regularly throughout the implementation of the large- and small-scale injection projects and site characterization projects with the lessons learned and updates to regulatory compliance requirements.

Infrastructure Goals

Table 4-3. Infrastructure Goals by Year

Year	Infrastructure Goals
2010	First large-scale injection of 1.5 million metric tons into a geologic formation for CO_2 storage in the United States.
2011	Complete the initial series of BPMs developed from lessons learned during the RCSP Validation Phase field tests and other geologic projects.
2012	Initiate assessment of additional small-scale injection projects that target depositional systems not previously explored for potential geologic storage.
2013	Initiate large-scale field projects in high priority geologic storage formation classes.
2014	Complete baseline assessment and begin injection in all RCSP large-scale injection projects.
2014	Inject at least 6 MMt of CO_2 into geologic storage formations.
2016	Update second version of BPMs for geologic storage from lessons learned from field projects and complete updates to regulatory compliance requirements.
2017	Complete assessment of high priority basins to allow project developers to assess storage capacity estimates with economic and demographic constraints.
2019	Complete post-injection operations in several of the RCSP proposed large-scale injection tests to validate the capability to adequately store CO_2 in regionally significant geologic formations in various depositional systems without impacting underground water sources.
2020	Upon completion of Phase III RCSP large-scale injection projects, projects will attain the RCSP goals, BPMs will be updated with final RCSP Phase III inputs based on post-injection monitoring, and a final geologic storage classification framework will be published.

B. National Carbon Sequestration Database and Geographic Information System

NATCARB is an interactive, relational database and geographic information system (GIS) that integrates CCS data from the RCSPs and other sources. Key geospatial data (including CO_2 stationary sources and potential geologic storage sites), interactive maps, and background information on the process of storing CO_2 are available free of charge to the public on the NATCARB website (http://www.netl.doe.gov/technologies/carbon_seq/natcarb/index.html).

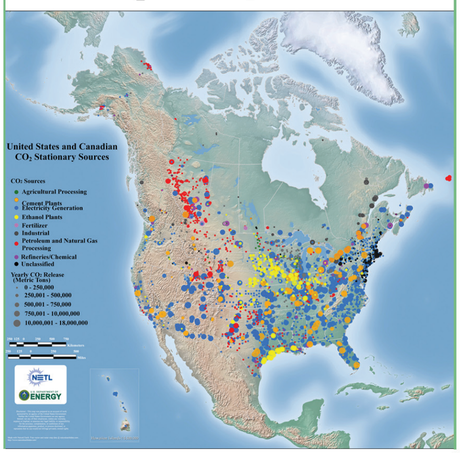
NATCARB started as a small, five-state project in 2000. The scope of the initial effort was to provide regional and national characterization of CO_2 storage opportunities. When the RCSPs formed in 2003, the NATCARB effort was expanded to develop the necessary framework to map the location of CO_2 stationary sources and characterize various geological formations to determine their CO_2 storage resource. At the end of the Characterization Phase, the RCSPs succeeded in developing a regional GIS to provide data to NATCARB, which was used to identify the most promising CO_2 storage opportunities in each RCSP region and raise awareness and support for CCS as a GHG mitigation option.

The RCSPs work to establish quantitative estimates of the geologic CO_2 storage potential in the subsurface environments of their regions. A consistent methodology was developed by NETL and members of the seven RCSPs to estimate the amount of CO_2 that can be stored in saline formations, unmineable coal areas, and oil and gas reservoirs. This methodology is based on volumetric methods for estimating subsurface volumes, in-situ fluid distributions, and fluid displacement processes. These methods are widely and routinely applied in petroleum, groundwater, underground natural gas storage, UIC disposal, and

CO_2 storage estimates. This methodology is developed to be consistent across the United States and Canada for a wide range of available data. This methodology was peer reviewed and a summary was published with results of the RCSPs' CO_2 storage assessment in the *2010 Carbon Sequestration Atlas of the United States and Canada – Third Edition (Atlas III)*.[3]

The production of Atlas III is the result of collaboration among carbon storage experts from local, state, and Federal agencies, as well as industry and academia. Atlas III provides a coordinated update of CCS potential across most of the United States and portions of Canada. The primary purpose of Atlas III is to update the CO_2 storage potential for the United States and Canada, and to provide updated information on the RCSPs' field activities. In addition, Atlas III outlines DOE's Carbon Sequestration Program, DOE's international CCS collaborations, worldwide CCS projects, and CCS regulatory issues. It also presents updated information on the location of CO_2 stationary source emissions and the locations and storage potential of various geologic storage sites; and further provides information about the commercialization opportunities for CCS technologies from each RCSP.

CO_2 Stationary Sources



Estimates of CO_2 Stationary Source Emissions and Estimates of CO_2 Storage Resources for Geologic Storage Sites

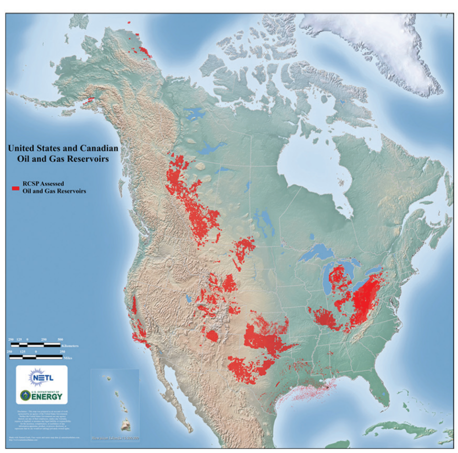
RCSP or Geographic Region	CO_2 Stationary Sources		CO_2 Storage Resource Estimates (billion metric tons of CO_2)				
	Quantity (million metric tons of CO_2)	Number of Sources	Saline Formations		Oil and Gas Reservoirs	Coal Areas	
			Low	High	---	Low	High
BSCSP	28	214	221	3,041	2	12	12
MGSC	266	229	12	160	1	2	3
MRCSP	699	353	46	183	17	1	1
PCOR	441	901	165	165	25	1	1
SECARB	1,043	908	908	12,527	32	33	75
SWP	315	341	219	3,013	62	1	2
WESTCARB	228	352	82	1,124	4	10	23
Non-RCSP	95	944	–	–	–	–	–
Total	**3,115**	**4,242**	**1,653**	**20,213**	**143**	**60**	**117**

Source: "2010 Carbon Sequestration Atlas of the United States and Canada – Third Edition (Atlas III)," DOE/NETL, November 2010

Geologic Storage Sites

Saline Formations

Oil and Gas Reservoirs



Coal Areas

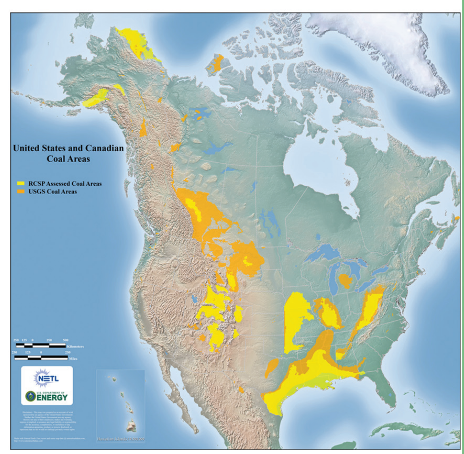


Figure 4-6. Estimates of CO_2 Stationary Emission Sources and Estimates of CO_2 Storage Resource for Geologic Storage Sites

[3] http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasIII/index.html.

As the Atlas is updated, the RCSPs provide improved data to NATCARB. NATCARB is organizing and enhancing the critical information about CO_2 stationary sources and developing the technology needed to access, query, model, analyze, display, and distribute CO_2 storage resource data related to carbon management. Users can estimate the amount of CO_2 emitted by CO_2 stationary sources (such as power plants, refineries, and other fossil fuel-consuming industries) in relation to geologic formations that can provide safe, secure CO_2 storage sites over long periods of time. Not only is the NATCARB server connected to all of the RCSPs, but data is also available from public servers, including the USGS-EROS center and the Geography Network. Major CO_2 stationary sources have been obtained from EPA databases, and data on major coal areas and coalbed methane (CBM) wells were obtained from the Energy Information Administration (EIA).

In 2009, NETL's ORD assumed responsibility for managing the NATCARB website and upgraded NATCARB into an informational research tool for a wide range of potential users. This effort included incorporation of web tools, such as Google Earth™ and Google Maps™, webpage development, data management and visualization, and public relations support to develop a web-based interface and mapping tools to track the progress of the RCSPs and communicate DOE efforts to the public. NETL will continue to improve the quality and expand the content of the NATCARB site to meet future needs. NETL will also work to improve the site for the general public and other users with simplified navigation features and enhanced online tools for visualization, query and analysis, and increased integration with the RCSPs.

NATCARB benefits many CCS stakeholders by providing improved online tools for the real-time display and analysis of CO_2 storage data. The NATCARB website receives more than 700 unique visitors every month from users around the world.

Currently, the NACAP effort is underway to expand NATCARB through an international collaboration to cover the United States, Canada, and Mexico. This international effort includes mapping of CO_2 stationary sources and geologic storage formations, methodology, data sharing, and the treatment of common border-boundary areas.

Lastly, NATCARB is also collaborating with the ARRA-funded site characterization projects within DOE's Carbon Sequestration Program. These projects are charged with examining the usefulness of potential geologic storage sites; augmenting existing data through coordination with a public database; and participating in technical working groups on best practices for site characterization and approving storage site selection. These projects are being incorporated into the NATCARB database.

Table 4-4. NATCARB Timeline

2011	Develop online NATCARB system integrating *Atlas III* data using advanced (Web 2.0) computing systems (e.g., MapServer, Google).
2013	Release *2012 Carbon Sequestration Atlas of the United States and Canada – Fourth Edition (Atlas IV)* and the "Methodology for Development of Geologic Storage Estimates for Carbon Dioxide."
2015 **2017** **2019**	Release updates to *Carbon Sequestration Atlas of the United States and Canada* that include the most recent collection of data and results from field projects.

V. Global Collaborations R&D

The last of the three elements is the Global Collaborations Element. This element includes ongoing collaborations with numerous global organizations to leverage U.S. expertise with other large-scale projects. These include participation in or relationships with a number of international demonstration projects, CSLF, and NACAP.

Supporting these projects directly benefits U.S. efforts to develop technologies and tools to meet the strategic goals of the program. In addition, these collaborations also provide a means to encourage technical transfer of the lessons learned between industry and academia to facilitate the adoption of these technologies in the field and to train personnel in the United States for future careers in the CCS industry throughout the world.

A. International Demonstrations

DOE is partnering with many international organizations to advance research in carbon storage. These projects are operating throughout the world (Figure 5-1). Benefits of U.S. scientists' participation range from opportunities to field test innovative technologies at commercial- and large-scale CCS operations around the world to representing U.S. expertise on multinational CCS investigative R&D teams. Table 5-1 summarizes selected highlights from these global partnerships.

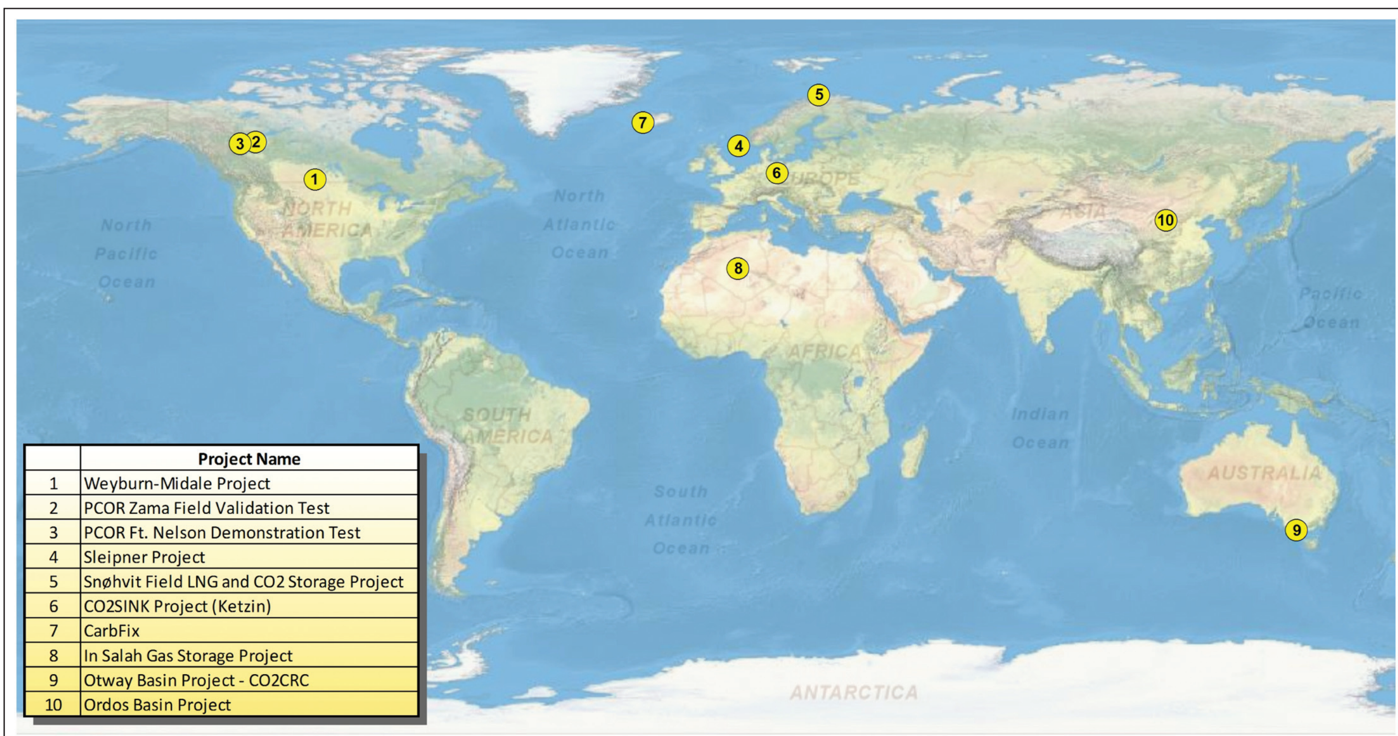


Figure 5-1. Map of DOE-Supported International CCS Projects

Table 5-1. DOE Support to International CCS Projects

Location/Project	Operations	Reservoir Storage Type	Operator/Partner	DOE Contribution
North America, Canada – Saskatchewan Weyburn-Midale	2.8 MMt CO_2/yr Commercial 2000	Oil Field Carbonate Enhanced Oil Recovery	Cenovus, Apache , Petroleum Technology Research Centre	DOE is supporting scientists to test multiple monitoring and simulation technologies.
North America, Canada – Alberta Zama Oil Field	25,000 Mt CO_2/yr, CO_2/Acid Gas Demo	Oil Field Carbonate Enhanced Oil Recovery	Apache (RCSP)	Supporting the Plains CO_2 Reduction (PCOR) Partnership to conduct monitoring and reservoir modeling of CO_2 injection into pinnacle reefs.
North America, Canada – British Columbia Fort Nelson	> 1 MMt CO_2/yr, 1.8 MMt Acid Gas/yr Large-scale Demo	Saline Carbonate Formation	Spectra Energy (RCSP)	Supporting PCOR Partnership to conduct monitoring and reservoir modeling studies.
Europe, North Sea – Norway Sleipner	1 MMt CO_2/yr Commercial 1996	Saline Marine Sandstone	StatoilHydro	Supporting the Scripps Institute of Oceanography, which is conducting time-lapse gravity surveys.
Europe, North Sea – Norway Snøhvit CO_2 Storage	700,000 Mt CO_2/yr Commercial 2008	Saline Marine Sandstone	StatoilHydro	Supporting the Lawrence Berkeley National Laboratory (LBNL) to simulate geo-mechanical conditions of the reservoir and caprock.
Europe, Germany CO_2SINK, Ketzin	60,000 Mt CO_2 Demo 2008	Saline Sandstone	GeoForschungsZentrum, Potsdam (GFZ)	Supported LBNL to deploy downhole monitoring technology based on thermal perturbation sensors.
Europe, Iceland CarbFix	CO_2 Stream from Hellisheidi Geothermal Power Plant	Saline Basalt	Reykjavik Energy	Supporting Columbia University Lamont-Doherty Earth Observatory to test tracer methods to assess trapping mechanisms in basalt formations.
Australia, Victoria Otway Basin	65,000 Mt CO_2 Stage I 2008	Gas Field and Saline Sandstone	CO_2CRC	Supporting scientists at LBNL to test multiple monitoring technologies at depleted gas field and saline formations.
Africa, Algeria In Salah Gas	1 MMt CO_2/yr Commercial 2004	Gas Field Sandstone	BP, Sonatrach, StatoilHydro	Supporting the Lawrence Livermore National Laboratory (LLNL) and LBNL to test field and remote sensing monitoring technologies and modeling geomechanical and geochemical reservoir processes.
Asia, China Ordos Basin	100,000 Mt CO_2/yr Model Phase	Ordos Basin	Shenhua Coal	Supporting West Virginia University and LLNL to assess capacity for storage, and simulating hydrogeologic and geochemical reservoir conditions.

B. Carbon Sequestration Leadership Forum

The CSLF is a ministerial-level carbon storage organization that is focused on the development of improved cost-effective technologies for the separation and capture of CO_2 for its transport and safe, long-term storage. An important CSLF goal is to improve CCS technologies through coordinated R&D with international partners and private industry. Formed in 2003, the CSLF has 23 members, including 22 countries and the European Commission. Joint efforts by DOE and the U.S. Department of State established the CSLF to facilitate the development of improved cost-effective technologies related to carbon capture, transportation, and long-term storage; promote the implementation of these technologies internationally; and determine the most appropriate political and regulatory framework needed to promote CCS on a global scale. More information on the CSLF and its activities can be found at: http://www.cslforum.org.

DOE continues to maintain a leadership role in the CSLF and provides support to 44 CCS projects worldwide – 36 domestic and 8 foreign projects (4 in Canada and 1 each in Germany, Australia, Algeria, and Norway). These 44 projects include 1 capture project, 22 storage projects, and 21 combined capture/storage projects. These DOE-supported projects are part of an online database compiled and maintained by NETL of approximately 240 total proposed, active, terminated, and canceled CCS projects worldwide as of October 2010. This database is intended to provide the public with information regarding efforts by various industries, public groups, and governments towards development and eventual deployment of CCS technology. A link to NETL's CCS projects database can be found at: http://www.netl.doe.gov/technologies/carbon_seq/database/index.html.

C. North American Carbon Atlas Partnership

NACAP is one of the key efforts of the North American Clean Energy Dialogue between the United States and Canada. NACAP is a joint CO_2 mapping initiative involving the United States, Canada, and Mexico. The purpose of NACAP is to create a North American carbon storage atlas that will speed the development of a comprehensive GIS database for CO_2 stationary sources and geologic reservoirs and help build collaboration among the three countries on CCS.

NACAP was launched in 2008 and is made up of four Working Groups: the Methodology Working Group, the Information Technology Working Group, the Policy Working Group, and the Atlas Development and Production Working Group. Current activities focus on the logistics behind preparing and publishing the NACAP Atlas; establishing the responsibility, management, and support structure involved; and defining a clear understanding of collaboration among the three North American countries.

D. U.S.-China Clean Energy Research Center

In November 2009, President Barack Obama and President Hu Jintao announced the establishment of the $150 million U.S.-China Clean Energy Research Center (CERC). The CERC facilitates joint research and development on clean energy technology (advanced coal technology, building energy efficiency, and clean vehicles) by teams of scientists and engineers from the United States and China. It is a flagship initiative funded in equal parts by the United States and China, with broad participation from universities, research institutions, and industry. The advanced coal technology, including a CCS consortium, addresses technology and practices for clean coal utilization and carbon capture, utilization, and storage.

VI. NETL's Office of Research and Development

NETL's ORD provides the Carbon Sequestration Program with an onsite "corporate laboratory," where fundamental and applied fossil energy R&D is led by Federal scientists and engineers. The Federal research staff leads teams from the Regional University Alliance (RUA) and other national laboratories to address key issues in the Core R&D program areas.

Important to ORD's success in its support to the Carbon Sequestration Program is the RUA, which consists of researchers at five major universities (Carnegie Mellon University, Pennsylvania State University, the University of Pittsburgh, Virginia Polytechnic University, and West Virginia University). The NETL-RUA provides a rapid route for NETL researchers to build strong research teams and collaborations with postdoctoral researchers, graduate students, professors, and undergraduate students over a wide range of disciplines in the area of carbon storage.

ORD offers a venue for participation in collaborative research and provides an evaluation of new technology concepts, products, and materials. Computational and Basic Sciences, Energy System Dynamics, Geological and Environmental Sciences, and Materials Science and Engineering are the four focus areas where ORD provides in-depth scientific expertise that can be applied to the development of new technologies, processes, and models essential for meeting long-term goals set for the Carbon Sequestration Program.

Relevant to the Carbon Sequestration Program, researchers in the Geological and Environmental Sciences (GES) Focus Area are working to support a range of technical needs of the Carbon Sequestration Program to help meets it goals for future capacity and storage assessments.

* Research on storage reservoirs is focused on improving the understanding of factors that impact storage resource and injectivity, thereby helping to improve regional and national estimates of resource potential.

- Seal integrity research is using NETL experimental facilities to assess the potential impact of geochemical and geomechanical processes on the integrity of wellbores and caprocks.

- Working with a variety of collaborators (including the RCSPs), NETL researchers are developing and field testing a suite of MVA technologies that improve the ability for early release detection and quantifying CO_2 plumes at storage sites (ranging from natural and engineered tracers to new geophysical methods); in addition, NETL investigated remote sensing methods that may assist in locating abandoned wells that provide release paths for stored CO_2.

- Using a variety of computational and experimental methods (spanning from micro-CT imaging to high pressure/temperature core flow units), NETL researchers are improving pore-scale to reservoir-scale predictive methods to provide accurate and reliable simulations in fractured reservoirs.

- Starting in 2009, ORD assumed responsibility for managing NATCARB and is upgrading the website into an informational and research tool for a wide range of potential users. This effort involves webpage development, data management and visualization, and public relations support to develop a web-based interface and mapping tools to track the progress of the RCSPs and communicate DOE efforts in carbon storage to the public.

Through ORD, research is being conducted on carbon capture to develop and evaluate breakthrough approaches that have the potential to significantly reduce the cost and energy intensity of CO_2 capture. Research focuses on approaches to energy production that use systems to remove CO_2 during energy production, rather than scrubbing it from a byproduct stream (pre-combustion capture).

- Integration of high fidelity models with systems level modeling combines steady-state process simulation with multiphysics-based equipment simulations, such as those based on computational fluid dynamics (CFD). These co-simulation capabilities enable design engineers to optimize overall process performance with respect to complex thermal and fluid flow phenomena arising in key plant equipment items—such as combustors, gasifiers, and turbines—and consider innovative carbon capture devices.

- To better focus the discovery, development, and deployment of pre-combustion capture technologies, ORD has established a CO_2 Capture Team to fully integrate the research efforts from computationally driven materials selection through process development and integration. This ensures that system and process considerations are factored into more fundamental research throughout the technology development cycle.

- The ORD CO_2 Utilization Team is focused on the development and evaluation of technologies that utilize CO_2 as a chemical feedstock for the production of fuels, plastics, aggregates, specialty chemicals, and other products with tangible value in the industrial product stream.

- The ORD Membrane Team will employ complementary experimental and computational research for developing effective CO_2 separation membranes. A multi-scale effort will be initiated to link models for gas transport at the membrane and device scales, with systems level analysis for the integration of membranes into power plants. This is closely linked to the computational efforts on the molecular level and experimental efforts in order to supply the information feedback (both ways) necessary to increase understanding and development of membrane systems.

To ensure a high level of quality and relevance for its projects, ORD conducts a comprehensive, annual peer review of its research projects. Teams of outside science and technology experts review research projects and provide a broad and comprehensive assessment of the current and planned R&D portfolio to affirm that ORD's efforts in carbon storage and other energy research continue to address pressing national R&D needs.

VII. Supporting Mechanisms

A. Other International Organizations

In addition to support provided to the international organizations and projects listed in Section V, in which DOE participates to advance international CCS efforts, DOE works closely with the IEAGHG, IEA, and North American partners through trilateral and bilateral agreements on energy with Canada and Mexico.

The IEAGHG is a multilateral organization that promotes energy security, economic development, and environmental protection throughout the world. IEAGHG experts have endorsed the efforts of DOE's RCSP Initiative and their large-scale tests as a successful approach to advance CCS in the United States, Canada, and internationally (http://www.netl.doe.gov/technologies/carbon_seq/partnerships/partnerships.html).

DOE directly supported the development of projects through these organizations and promotes the transfer of technologies from the Core R&D and lessons learned from the RCSPs to support global deployment of CCS technologies.

DOE/NETL believes that the economic rewards achieved through new business opportunities in the United States and abroad will provide leverage to assist other countries to engage in CO_2 storage projects.

B. Interagency and State Coordination

The program team has worked with different Federal and state agencies to help resolve regulatory issues that have not been addressed for wide-scale deployment of CCS technologies. This includes interacting with EPA; the U.S. Department of Interior's (DOI) Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE); DOI's Bureau of Land Management (BLM) and USGS; the Interstate Oil and Gas Compact Commission (IOGCC); Ground Water Protection Council (GWPC); and the U.S. Department of Transportation (DOT) on issues related to CO_2 storage and transport. The objective of these efforts to work with other agencies is to continue to provide results from research that help inform regulatory decision making. The methodologies developed and data collected by the program are also providing support to BLM, BOEMRE, and USGS as they determine the potential for Federal lands to play a role in developing CCS opportunities onshore and offshore.

With regard to CO_2 storage, activities with these agencies include: participating in EPA's CCS Working Group, participating in the preparation of several BLM reports to Congress, assisting BOEMRE with developing rules for offshore CO_2 injection, examining the legal and regulatory framework for CO_2 storage with the IOGCC, and examining state regulatory program data management for CO_2 storage with the GWPC. The Carbon Sequestration Program Team has also collaborated with DOT, the Federal Energy Regulatory Commission (FERC), the National Association of Regulatory Utility Commissioners (NARUC), and the Surface Transportation Board (STB) to examine the regulatory framework for CO_2 pipeline siting, operation, and tariffs, and has participated in the IOGCC Pipeline Transportation Taskforce on CO_2 pipelines for carbon storage. All of this involves more than 20 states and Canadian provinces that are members of the IOGCC.

On February 3, 2010, President Obama sent a memorandum to the heads of 14 Executive Departments and Federal Agencies establishing an Interagency Task Force on CCS. On August 12, 2010, the Task Force delivered a series of recommendations to President Obama on overcoming the barriers to the widespread, cost-effective deployment of CCS within 10 years. The report concludes that CCS can play an important role in domestic GHG emissions reductions while preserving the option of using abundant domestic fossil energy resources. However, widespread, cost-effective deployment of CCS will occur only if the technology is commercially available at economically competitive prices and supportive national policy frameworks are in place. This program plan supports the findings of the CCS Task Force in establishing key areas for CCS that need to be addressed to help make advanced technologies available by 2020 at reasonable costs and could be deployed widely across the U.S. economy.

C. Systems and Benefits Analysis

NETL's OPPA conducts analyses to demonstrate how R&D activities support national and international priorities related to energy supply, energy use, and environmental protection (http://www.netl.doe.gov/technologies/carbon_seq/systems.html). OPPA examines the following three areas of analysis (with respect to the Carbon Sequestration Program): (1) *Systems* – places research objectives (e.g., improvements in the cost and efficiency of CCS technologies) in the context of their impacts on commercial power generation systems and other industrial processes; (2) *Policy* – places CCS in the context of regulatory compliance and environmental policy; and (3) *Benefits* – combines technology and policy to show economic and environmental costs and benefits that a successful Sequestration R&D Program will provide both domestically and internationally.

D. University and Research Laboratory Collaborations

NETL has formed the RUA for energy technology innovation in partnership with a consortium of five nationally recognized universities. The RUA consists of Carnegie Mellon University, West Virginia University, the University of Pittsburgh, Pennsylvania State University, and Virginia Tech. The RUA research program assists NETL in conducting both basic and applied energy and environmental research that support DOE's mission to advance U.S. national, economic, and energy security goals.

The purpose of NETL's laboratory collaboration is to bridge the basic and applied gap to develop the strong science base that ensures successful large-scale field projects for geologic CO_2 storage. Specifically, NETL's Advanced Research (AR) Program is leading a multi-national-lab effort on science-based risk assessment; the National Risk Assessment Partnership (NRAP) includes five DOE national laboratories – NETL, LBNL, LLNL, Los Alamos National Laboratory (LANL), and Pacific Northwest National Laboratory (PNNL) – that are developing a robust, defensible, science-based method for quantifying potential risks associated with the long-term CO_2 storage. NETL's AR Program is also leading an effort through the Carbon Capture and Simulation Initiative (CCSI), which brings the national laboratories together to leverage their simulation capabilities to develop virtual simulations of integrated CCS systems with different power plant configurations. It is expected that this effort will allow researchers to simulate an intermediate scale of research and accelerate demonstration of promising CO_2 capture technologies.

Contact Information

The NETL website (http://www.netl.doe.gov) offers extensive information about the components of DOE's Carbon Sequestration Program. The website provides an extensive program overview webpage with details about the five technical Core R&D focus areas, Systems Analyses capabilities, a FAQ information portal, information about the RCSPs with links to their websites, and an extensive reference shelf. Links to numerous resources can be accessed via the Carbon Sequestration Reference Shelf on the NETL website. Each of the categories on the Carbon Sequestration Reference Shelf has a variety of documents posted for easy access to current information. Once at: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/refshelf.html, click on a category to view all materials related to the following:

- The Carbon Sequestration Newsletter (http://listserv.netl.doe.gov/mailman/listinfo/sequestration)
- Major Carbon Sequestration Educational Resources
- Program Overview Presentations
- Program Reports, Plans, and Roadmaps
- Journals and Scientific Articles
- Conference Proceedings and Presentations
- Project Descriptions
- Program Fact Sheets
- Regulatory and Policy Issues
- Systems Analysis
- Peer Review
- Best Practice Manuals

To learn more about DOE's Carbon Sequestration Program, please contact:

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