Carbon Storage Program

2010–2011

ACCOMPLISHMENTS

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Disclaimer

Carbon Storage Program 2010–2011 Accomplishments

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List of Acronyms and Abbreviations

ADEM	Alabama Department of Environmental Management
ANL	Argonne National Laboratory
ARRA or Recovery Act	American Recovery and Reinvestment Act of 2009
ASME	American Society of Mechanical Engineers
BLM	U.S. Department of Interior's Bureau of Land Management
BOEM	U.S. Department of Interior's Bureau of Ocean Energy Management
BPM	Best Practice Manual
BSCSP	Big Sky Carbon Sequestration Partnership
CBM	Coalbed Methane
CCS	Carbon Capture and Storage
CCSI	Carbon Capture and Storage Institute
CCUS	Carbon Capture, Utilization, and Storage
CdSe	Cadmium-Selenide
CERC	U.S.-China Clean Energy Research Center
CEU	Continuing Education Units
CH_4	Methane
CLA	City of Los Angeles
CO_2	Carbon Dioxide
CO_2CRC	Cooperative Research Centre for Greenhouse Gas Technologies
COE	Cost of Electricity
CSLF	Carbon Sequestration Leadership Forum
CUB	Coal Utilization Byproduct
DOE	U.S. Department of Energy
DOI	U.S. Department of Interior
DOT	U.S. Department of Transportation
EC	European Commission
ECBM	Enhanced Coalbed Methane
EOR	Enhanced Oil Recovery
EPA	U.S. Environmental Protection Agency
ER	Enhanced Recovery
FE	U.S. DOE's Office of Fossil Energy
FERC	Federal Energy Regulatory Commission
FGD	Flue Gas Desulfurization
FONSI	Finding of No Significant Impact
FWP	Field Work Proposal
GFZ	GeoForschungsZentrum, Potsdam
GHG	Greenhouse Gas
GIS	Geographic Information System
GWPC	Ground Water Protection Council
H_2O	Water
H_2S	Hydrogen Sulfide
ICCS	Industrial Carbon Capture and Storage
IEA	International Energy Agency
IEA GHG	International Energy Agency Greenhouse Gas R&D Programme
IEP	Innovations for Existing Plants
IGCC	Integrated Gasification Combined Cycle
IOGCC	Interstate Oil and Gas Compact Commission

LBNL ..... Lawrence Berkeley National Laboratory

LLNL ..... Lawrence Livermore National Laboratory

MGSC ..... Midwest Geological Sequestration Consortium

MOU ..... Memorandum of Understanding

MRCSP ..... Midwest Regional Carbon Sequestration Partnership

MSU ..... Montana State University

MVA ..... Monitoring, Verification, and Accounting

MW ..... Megawatts

NACAP ..... North American Carbon Atlas Partnership

NACSA ..... North American Carbon Storage Atlas

NAEWG ..... North American Energy Working Group

NARUC ..... National Association of Regulatory Utility Commissioners

NATCARB ..... National Carbon Sequestration Database and Geographic Information System

NEPA ..... National Environmental Policy Act

NETL ..... National Energy Technology Laboratory

NGCC ..... Natural Gas Combined Cycle

NRCan ..... National Resources Canada

OPPA ..... Office of Program Planning and Analysis

ORD ..... Office of Research and Development

PCOR ..... Plains CO_2 Reduction Partnership

PFT ..... Perfluorocarbon Tracer

PNNL ..... Pacific Northwest National Laboratory

PSL ..... Polymer Synthesis Laboratory

PTTF ..... Pipeline Transportation Task Force

R&D ..... Research and Development

RCSP ..... Regional Carbon Sequestration Partnership

RD&D ..... Research, Development, and Demonstration

RUA ..... Regional University Alliance

SECARB ..... Southeast Regional Carbon Sequestration Partnership

SGR ..... South Georgia Rift

SSEB ..... Southern States Energy Board

STB ..... Surface Transportation Board

STEP ..... Sequestration Training and Education Program

SWP ..... Southwest Regional Partnership on Carbon Sequestration

THMCB ..... Thermal, Hydrologic, Mechanical, Chemical, and Biological

TiO_2 ..... Titanium Dioxide

UIC ..... EPA's Underground Injection Control Program

UNDEERC ..... University of North Dakota Energy and Environmental Research Center

UNFCCC ..... United Nations Framework Convention on Climate Change

USDW ..... Underground Sources of Drinking Water

USGS ..... U.S. Geological Survey

VSP ..... Vertical Seismic Profiling

WESTCARB ..... West Coast Regional Carbon Sequestration Partnership

WWG ..... Water Working Group

ZERT ..... Zero Emissions Research and Technology

Carbon Storage Program Focus

Develop a suite of technologies that can safely and economically store and utilize CO_2 from coal-based energy systems, permanently reducing greenhouse gas emissions to the atmosphere as contributors to global climate change

Carbon Storage Program 2010-2011 Accomplishments

The mission of the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL)-managed Carbon Storage Program is to create a public benefit by discovering and developing methods to economically and permanently store greenhouse gas (GHG) emissions from the combustion of fossil fuels. The technologies developed through the program will be used to maintain fossil fuel power plants as viable, clean sources of electric power.

The program is focused on developing technologies that can achieve 99 percent of carbon dioxide (CO_2) storage permanence and improve the ability to determine the storage resource in geologic formations. The program is also focused on integrating lessons learned from the Core R&D technology development efforts and field experience from the Regional Carbon Sequestration Partnerships (RCSPs) into Best Practice Manuals (BPMs) for industry to utilize. The goal of DOE research in the area of geologic carbon storage is to develop technologies to safely, permanently, and cost-effectively store CO_2 in suitable geologic formations; monitor its movement and behavior; and develop tools and protocols to improve efficiency of storage operations. This involves developing an improved understanding of CO_2 flow and trapping mechanisms within geologic formations that can support the development of improved and novel technologies for site construction, reservoir engineering, and well construction. Experience gained from field tests will facilitate the development of carbon capture, utilization, and storage (CCUS) best practices for site development, operations, and closure to ensure that CO_2 storage is secure and does not impair the geologic integrity of underground formations. Additional information on this effort can be found in NETL's Carbon Storage Technology Program Plan.

DOE is moving towards the terminology carbon capture, utilization, and storage (CCUS) to replace the term CCS. In CCUS, "utilization" encompasses the use of CO_2 for economic benefits prior to its safe and permanent storage, including its use with enhanced recovery.

This goal will be accomplished by reducing the cost of these technologies and conducting demonstrations based on sound science to ensure that commercial applications can reliably and safely transport, store, and monitor CO_2 injected into geologic formations.

> "CCS can play an important role in domestic GHG emissions reductions while preserving the option of using abundant domestic fossil energy resources."
>
> —Report of the Interagency Task Force on Carbon Capture and Storage

The Carbon Storage Program consists of a portfolio of laboratory and field research and development (R&D) projects focused on technologies with the potential for reducing GHG emissions. In addition to these projects, DOE's participation in initiatives, such as the Carbon Sequestration Leadership Forum (CSLF) and the International Energy Agency Greenhouse Gas R&D Programme (IEA GHG), promotes the global implementation of CCUS technologies. The program also undertakes global collaborations through the support of international projects, including the Weyburn project in Canada, the In Salah project in Algeria, the Sleipner and Snøhvit projects in Norway, Australia's Otway project, the German CO_2SINK project, and Canada's Fort Nelson and Zama Acid Gas Injection projects.

The Carbon Storage Program is closely coordinated with the Carbon Capture Program at NETL. The overall goal of this program is to develop advanced technologies that achieve 90 percent CO_2 capture at less than a 10 percent increase in the cost of electricity (COE) of pre-combustion capture for integrated gasification combined cycle (IGCC) power plants and less than a 35 percent increase in COE of post- and oxy-combustion capture for new and existing conventional coal-fired power plants. Detailed information on this program can be found in the report titled, "DOE/NETL Advanced Carbon Dioxide Capture R&D Program: Technology Update."

Additionally, NETL's Office of Research and Development (ORD) conducts onsite research that provides the scientific basis for carbon storage options through its Geological and Environmental Systems Focus Area, which seeks to assess the resource, suitability, and permanence of potential carbon storage reservoirs; to assess the ability of unconventional reservoirs to produce gas and oil and to assist in that production; and to improve environmental performance of existing power plants. Also, research to understand and improve CO_2 capture and utilization are conducted through ORD's three other Focus Areas: Energy Systems Dynamics, Computational and Basic Science, and Materials Science and Engineering. NETL's Office of Program Planning and Analysis (OPPA) conducts analyses to demonstrate how R&D activities support national and international priorities related to energy supply, energy use, and environmental protection. OPPA conducts the following three types of analyses (with respect to the Carbon Storage Program): (1) Systems – places research objectives (e.g., improvements in the cost and efficiency of CO_2 reuse technologies) in the context of their impacts on commercial power generation systems and other industrial processes; (2) Policy – places CCUS in the context of regulatory compliance and environmental policy; and (3) Benefits – combines technology and policy options to show economic and environmental costs and benefits that a successful Carbon Storage Program will provide domestically.

Furthermore, the Carbon Storage Program is coordinated with a number of states, governmental agencies, national laboratories, universities, and private companies. For example, the program's Regional Carbon Sequestration Partnership (RCSP) Initiative includes representatives from more than 400 organizations. The program is coordinated with agencies, such as the U.S. Environmental Protection Agency (EPA); the U.S. Department of Interior's (DOI) Bureau of Ocean Energy Management (BOEM); DOI's Bureau of Land Management (BLM); 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. DOE and EPA were the co-leads of the Interagency Task Force on CCS, which was formed in 2010 (see text box for more information).

With regard to CO_2 storage, specific activities with these agencies include: participating in EPA's CCS Working Group, participating in the preparation of several BLM reports to Congress, engaging BOEM 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 Storage Program is also coordinated with DOT, the Federal Energy Regulatory Commission (FERC), the National Association of

Interagency CCS Task Force

Starting in February 2010, 14 Executive Departments and Federal Agencies established an Interagency Task Force on Carbon Capture and Storage.

The Task Force's goal was to develop a comprehensive and coordinated Federal strategy to speed the commercial development and deployment of clean coal technologies. The Task Force, co-chaired by DOE and the EPA, was charged with proposing a plan to overcome the barriers to the widespread, cost-effective deployment of CCS within 10 years, with a goal of bringing 5 to 10 commercial demonstration projects online by 2016. The final report was published in August 2010. More information is available on the CCS Task Force website.

Regulatory Utility Commissioners (NARUC), and the Surface Transportation Board (STB) to examine the regulatory framework for CO_2 pipeline siting, operation, and tariffs, and program managers have participated in the IOGCC Pipeline Transportation Taskforce on CO_2 pipelines for carbon storage.

NETL's Carbon Storage Program managers are developing a technology portfolio of safe, cost-effective, commercial-scale CO_2 storage and mitigation technologies that will be available for commercial deployment. NETL's primary carbon storage R&D objective is to improve the understanding of factors affecting CO_2 storage permanence, resource, and safety in geologic formations and terrestrial ecosystems.

NETL's Carbon Storage Program received $70 million from the American Recovery and Reinvestment Act of 2009 (Recovery Act or ARRA). These funds are being used for (1) Geologic Storage Site Characterization projects ($50 million), and (2) to provide training opportunities at universities and to establish regional training centers with the goal of creating a qualified carbon storage workforce in the United States ($20 million). In 2010, an additional $50 million was provided to the 10 site characterization projects to augment the work that the projects are performing. This additional funding will allow these projects to better characterize the geology for storage opportunities for industrial sources of CO_2. The projects now involve the drilling of deeper wells, as well as additional wells; the collection of significantly more core samples, as well as additional geophysical samples and data; and include more extensive reservoir modeling. These efforts complimented the existing goals for the program. Sixty projects were awarded with the Recovery Act funds.

There have been significant ARRA accomplishments to date. For example, as of the end of 2011, there were more than 180 students and professionals trained with more than 150,000 hours of research for future work in the CCUS industry.

Benefits of ORD Work

NETL's ORD provides the Carbon Storage 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 focus areas.

Important to ORD's success in its support to the Carbon Storage Program is NETL's RUA, which consists of researchers at five major universities (Carnegie Mellon University, Pennsylvania State University, the University of Pittsburgh, Virginia Tech, and West Virginia University). NETL-RUA provides a rapid route for NETL researchers to build strong research teams and collaborations with post-doctoral 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. ORD provides in-depth scientific expertise in the following four focus areas: Computational and Basic Sciences, Energy System Dynamics, Geological and Environmental Sciences, and Materials Science and Engineering. This expertise can be applied to the development of new technologies, processes, and models essential for meeting long-term goals set for the Carbon Storage Program.

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.

From its inception through 2012, DOE's Carbon Storage Program budget had increased 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 $115 million in 2012 (Figure 1). 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 more than 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.

The recent decrease in funding maintains funding for the RCSPs and reduces the funding levels for small- and large-scale field tests in other promising geologic storage classes. The decrease in funding for other parts of the Carbon Storage Program gives greater priority to near-term research areas to meet goals for safe, permanent storage.

Prior to FY2008, DOE/NETL's CO_2 emissions control R&D effort was conducted under the Carbon Storage Program. In FY2008, NETL's Innovations for Existing Plants (IEP) Program redirected its focus to include post- and oxy-combustion CO_2 emissions control for existing pulverized coal-fired plants. In FY2012, this focus expanded to include pre-combustion capture, which had remained under the Carbon Storage Program through FY2011.

The Carbon Storage Program consists of three main elements: Core R&D, Infrastructure, and Global Collaborations (Figure 2).

- **Core R&D** – The Core R&D Element is focused on developing new storage technologies to the point of pre-commercial deployment and includes core research performed externally under cost-shared, industry participation development projects/ research grants, and internally by NETL's scientists and engineers. The Core R&D element is comprised of four technical focus areas: (1) Geologic Storage;

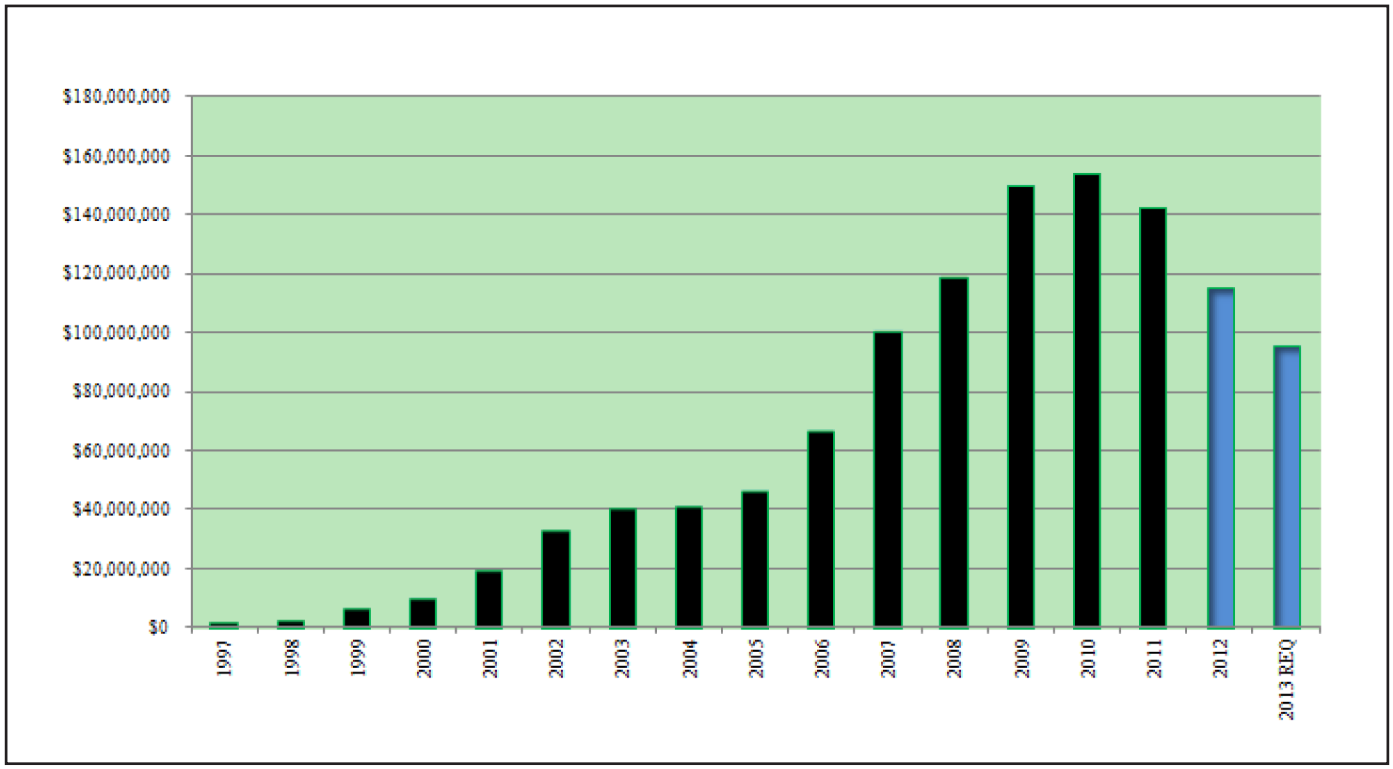


Figure 1: Carbon Storage Program Budgets from FY1997-2013 REQ

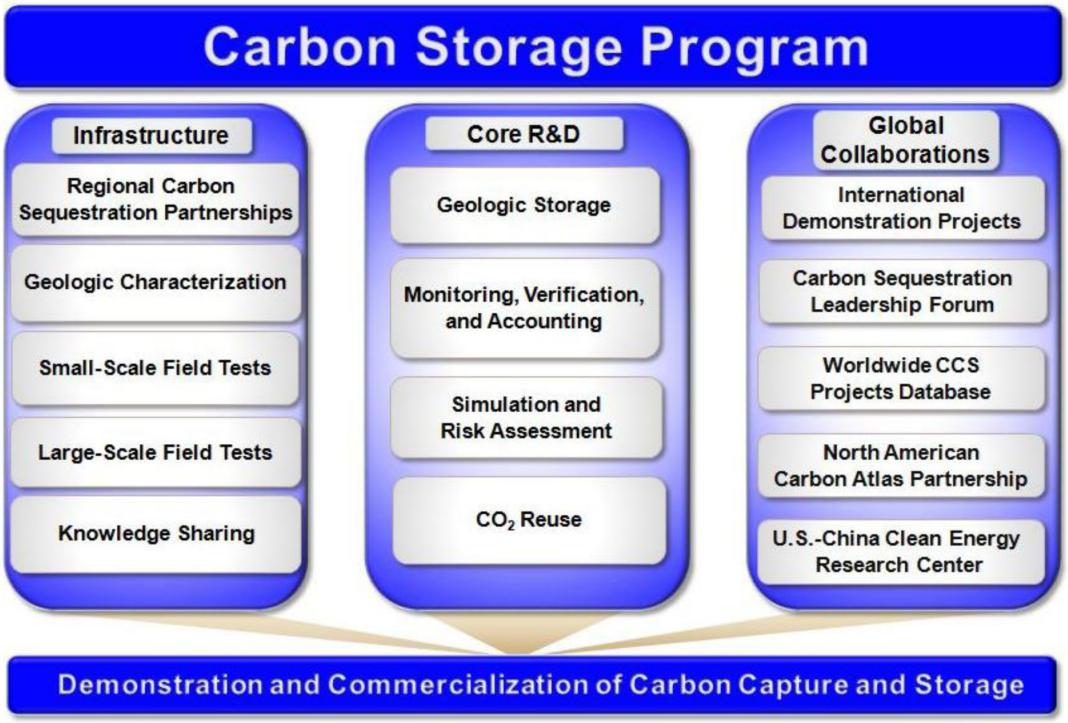


Figure 2: Carbon Storage Program Overview

(2) Monitoring, Verification, and Accounting (MVA); (3) Simulation and Risk Assessment; and (4) CO_2 Reuse. Research activities range in scope from laboratory-scale research through pilot-scale operations. The research in each area is based on the need to develop and apply technological solutions ready for large-scale testing.

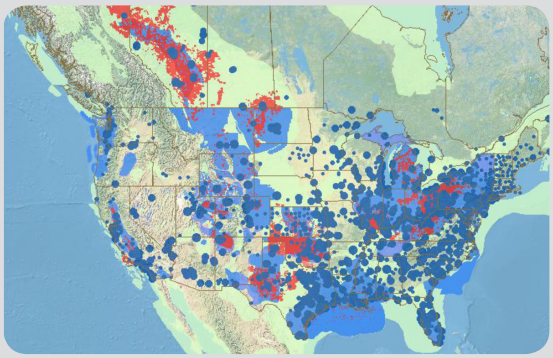


Figure 3: NATCARB Viewer

The National Carbon Sequestration Database and Geographic Information System (NATCARB) is a geographic information system (GIS)-based tool developed to provide a view of CCS potential.

NATCARB organizes and enhances the critical information about CO_2 stationary sources and develops the technology needed to access, query and model, analyze, display, and distribute CO_2 storage resource data. Data are generated, maintained, and enhanced locally at each RCSP, or at specialized data warehouses and public servers (e.g., USGS-EROS Data Center, U.S. Environmental Protection Agency [EPA], and the Geography Network), and assembled, accessed, and analyzed in real-time through a single geoportal.

- **Infrastructure** – The Infrastructure Element is focused on R&D initiatives to advance geologic CO_2 storage toward commercialization. DOE determined early in the program's development that addressing CO_2 mitigation on a regional level is the most effective way to address differences in geology, climate, population density, infrastructure, and socioeconomic development. This element includes efforts designed to support the development of regional infrastructure for CCUS.

- **Global Collaborations** – The Global Collaborations Element includes ongoing partnerships 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, the Carbon Sequestration Leadership Forum (CSLF), the U.S. China Clean Energy Research Center (CERC), and the North American Carbon Storage Atlas Partnership (NACAP). Supporting these projects directly benefits U.S. efforts to develop technologies and tools to meet the strategic goals of the Carbon Storage Program. In addition, these collaborations also provide a means to encourage transfer of lessons learned and knowledge sharing 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 CCUS industry throughout the world, and particularly in North America.

Core R&D

The Core R&D Element focuses on developing new CCUS technologies to a pre-commercial demonstration level. The Core R&D Element includes four technical focus areas: (1) Geologic Storage; (2) Monitoring, Verification, and Accounting (MVA); (3) Simulation and Risk Assessment; and (4) CO_2 Reuse.

The Core R&D Element is implemented through: (1) cost-shared cooperative agreements and grants with industry and academic institutions; (2) field work research at other national laboratory complexes; and (3) research at NETL's ORD. NETL conducts onsite research that provides the scientific basis for carbon storage options through its Geological and Environmental Systems research focus area.

Key R&D activities for this element include:

Geologic Storage – Geologic CO_2 storage involves the injection of supercritical CO_2 into deep geologic reservoirs (injection zones) overlain by competent sealing formations that will prevent the CO_2 from migrating upwards. Current research and field studies are focused on developing better understanding of the 11 major types of geologic storage reservoir classes, each having their own unique opportunities and challenges. The different storage reservoir classes include: clastic deltaic, coal/shale, fluvial, alluvial, strandplain, turbidite, eolian, lacustrine, shelf, carbonate shallow shelf, and reef. Basaltic interflow zones are also being considered as potential reservoirs. These storage reservoirs contain fluids that may include natural gas, oil, or saline water; all of which will interact with CO_2 and affect storage. DOE is investigating the challenges related to CO_2 storage capability in more conventional clastic and carbonate reservoirs, as well as unconventional reservoirs (unmineable coal seams, organic-rich shales, and basalts).

The Core R&D Element includes University Geologic Sequestration Training Projects funded under the Recovery Act. These projects focus on providing education and training activities to aid in the development of a future generation of geologists, scientists, and engineers that will provide the human capital and skills required for the implementation and deployment of large-scale CCS.

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 recovery (ER). Natural analogs to CO_2 storage exist throughout the United States, where CO_2 has been naturally trapped in confined geologic layers and structures deep below the surface of the Earth. Lessons learned from natural systems, ER operations, gas storage, and sponsored CO_2 storage projects are all important for developing storage technologies for a future CCUS industry.

Monitoring, Verification, and Accounting (MVA) – An MVA program is designed to confirm permanent storage of CO_2 in geologic formations through monitoring capabilities that are 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, abandoned, and monitoring

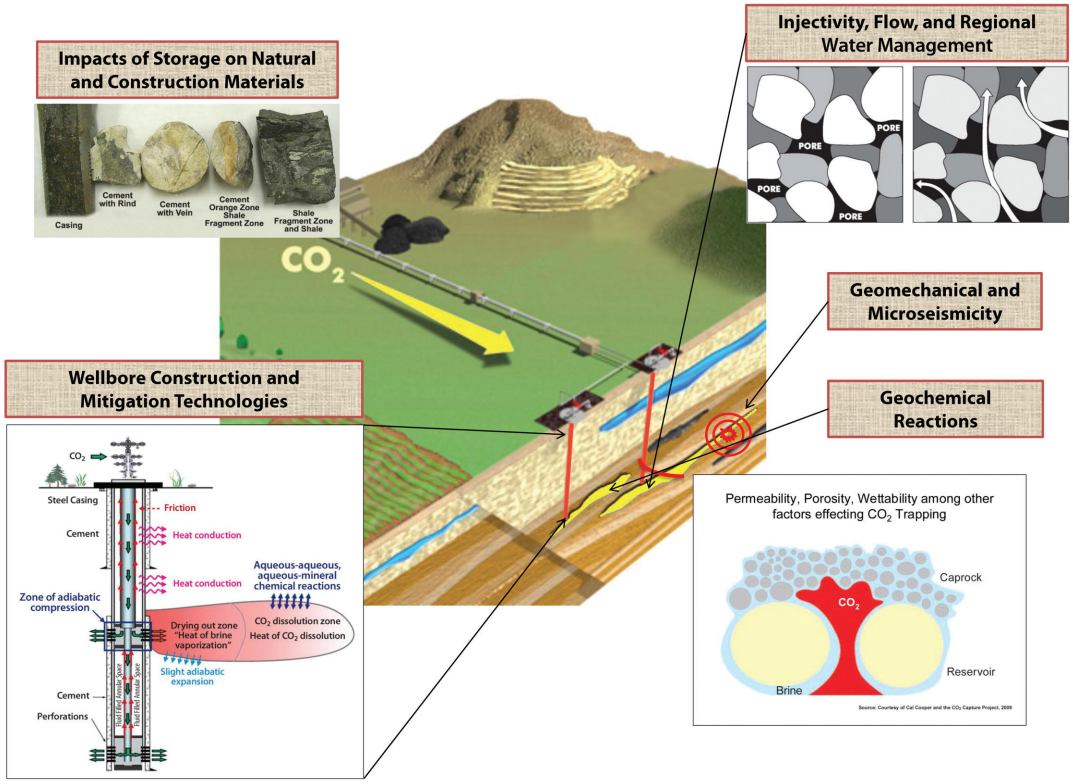


Figure 4: Diagram of Geologic Storage Concept Highlighting Current Research Areas

Geologic Storage Research Goals

NETL's Core R&D research in the Geologic Storage Focus Area is based on developing the ability to characterize a geologic formation before CO_2-injection to be able to predict the CO_2 storage resource and to develop CO_2 injection techniques that achieve optimal use of the pore space in the reservoir and avoid fracturing the caprock (Figure 4). Site characterization and injection techniques are interrelated because improved formation characterization will help determine the best injection procedure.

In collaboration with its partners in the Regional University Alliance, activities performed by NETL's ORD are aimed at understanding chemical, biological, and mechanical processes of the subsurface environment and their potential impact on storage performance. Samples for many of the subtasks are obtained from RCSP field sites, which is mutually beneficial to the RCSP and Core R&D Programs. The benefits include the development of more accurate models to predict subsurface behavior and evaluate potential storage formations, which addresses both goals of 99 percent storage permanence and improved resource assessment accuracy. In addition, NETL's ORD is working to address the goal of predicting storage capacity to ±30 percent accuracy by further developing estimation methodologies. This work includes a comparison of existing methodologies and the development of methodologies for enhanced oil recovery and unconventional formations, like coal and shale.

wells are structurally sound and that CO_2 will remain within the injection formation. Federal greenhouse gas accounting regulations under the Safe Drinking Water Act and Clean Air Act require monitoring 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 through monitoring to satisfy operating requirements under EPA's Underground Injection Control (UIC) Program to ensure that potable groundwater sources and sensitive ecosystems are protected. More information on available MVA techniques is available in DOE's "Best Practices for Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations."

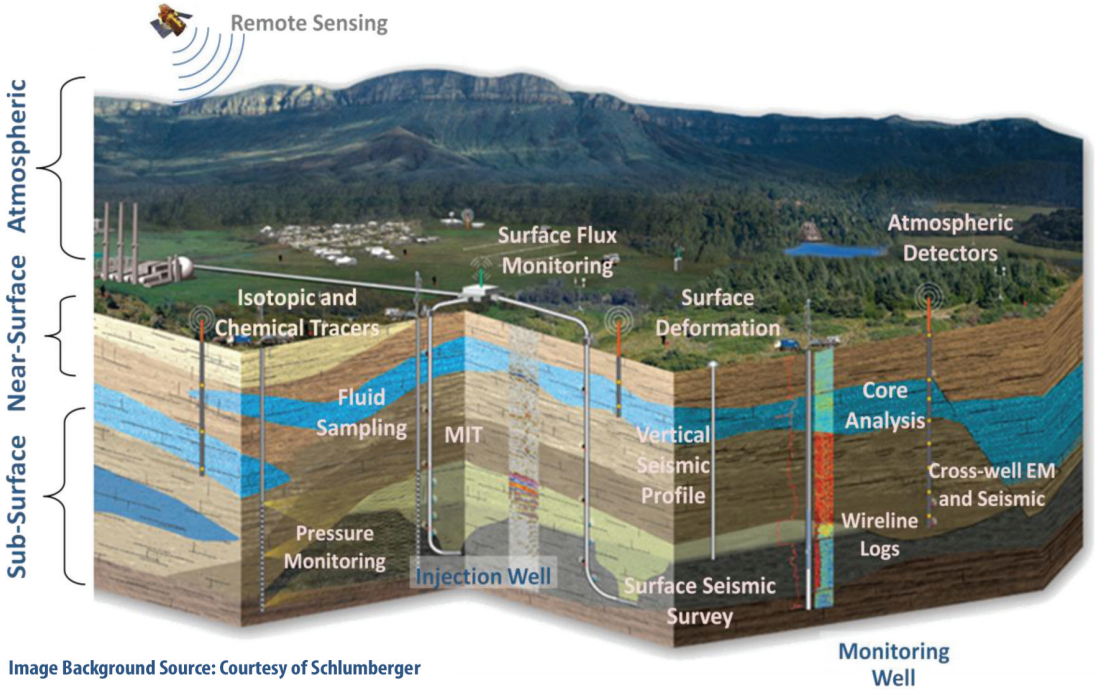


Figure 5: MVA Tools Utilized Throughout a Geologic System

MVA Research Goals

It is necessary to improve existing monitoring technologies, enhance the development of novel systems, and integrate protocols to satisfy regulations to track the fate of subsurface CO_2 and quantify any movement of CO_2 from the target formations. The Carbon Storage Program is focusing on the development of MVA technologies and protocols that are broadly applicable in different geologic storage formations and have sufficient accuracy to account for greater than 99 percent of all CO_2 injected into the storage formation (Figure 5). 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. Coupled with the increased understanding of these systems and reservoir models, MVA tools will help in the development of one of DOE's goals to quantify storage resource, as well as validate the efficiency of storage operations.

The Carbon Storage Program has a timeline and goals provided in the Program Plan with regard to development of technologies to track the fate of subsurface CO_2 and ensure 99 percent storage permanence. In collaboration with its partners in the Regional University Alliance, NETL's ORD is developing techniques and modeling to optimize monitoring networks. This activity includes monitoring the near surface, groundwater, and deep subsurface for direct and indirect indications of fluid migration.

Simulation and Risk Assessment – The Simulation and Risk Assessment Focus Area is an integrated effort to develop advanced simulation models of the subsurface and to integrate the results into a risk assessment that includes both technical and programmatic risks. As the simulation models are refined with new data, the uncertainty surrounding the identified risks decreases, which in turn provides a more accurate risk assessment and mitigation plan for each project site. Both qualitative and quantitative protocols will be developed to ensure the safe and permanent storage of CO_2. Results from the simulation models will be incorporated into risk assessments on a project-by-project basis and on a larger basin-scale.

As CCUS 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 also can be used to: (1) predict the thermal impacts and hydrologic flow of CO_2 in the target formation; geochemical and thermal changes that may occur in the storage formation; (2) geomechanical effects on the target formation, seals, and potential release pathways, such as faults, fractures, and wellbores; and (3) the effect of biological responses in the presence of supercritical CO_2.

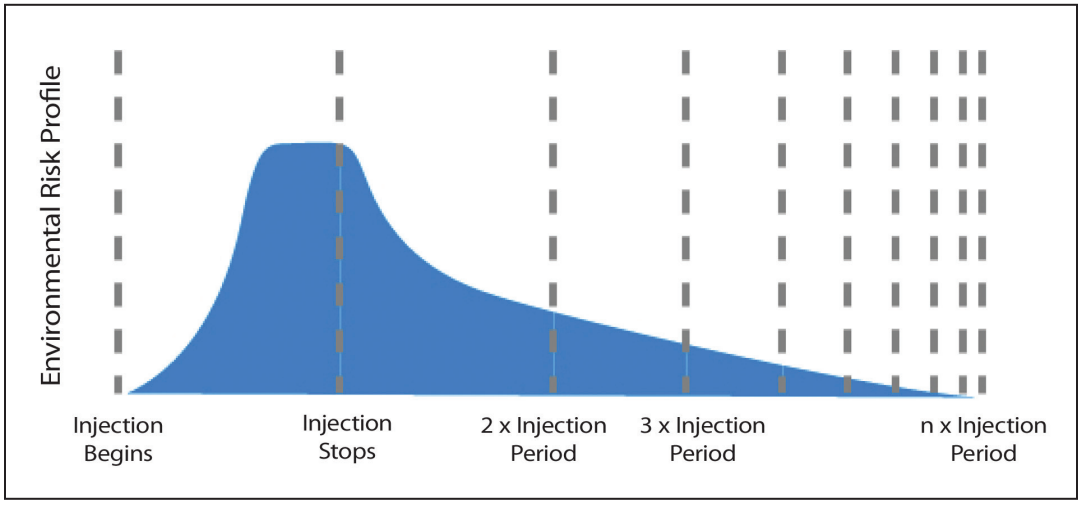


Figure 6: Schematic Risk Profile for A CO_2 Storage Project (Benson, 2007; WRI Presentation)

Simulation and Risk Assessment Research Goals

A significant amount of work has been completed by industry and academia to develop simulators for CO_2 that couple thermal, hydrologic, mechanical, chemical, and biological (THMCB) processes involved in CO_2 storage. 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 better represent THMCB processes.

There are key fundamental parameters and processes that have a potential impact on all carbon storage environments. In collaboration with its partners in the Regional University Alliance, NETL's ORD is working to improve the quantitative understanding of the ability to model key chemical reaction kinetics and thermodynamic properties of fluids (CO_2/brine). The benefits include more accurate models to predict subsurface behavior and evaluate potential storage formations, but at a more universal fundamental level rather than a site-specific level (Figure 6).

A risk assessment 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 issues with a storage site and developing mitigation procedures so that immediate action can be implemented should an issue arise. Risk assessment also helps determine long-term project costs and potential liabilities in support of decisions on decommissioning and long-term stewardship. Carbon dioxide storage projects will generally face two primary categories of risks: (1) programmatic risks (including resource and management risks) that may inhibit project progress or increase costs, and (2) storage (technical) risks inherent to the scientific and engineering objectives of a storage project.

CO_2 Reuse – Carbon dioxide (CO_2) reuse efforts focus on pathways and novel approaches for reducing CO_2 emissions by developing beneficial uses for the CO_2 that can be used in applications that could generate significant benefits (Figure 7). It is possible to develop alternatives that can use captured CO_2 or convert it to useful products such as chemicals, cements, or plastics. Revenue generated from the utilized CO_2 could also offset a portion of the CO_2 capture cost.

Another aspect of CO_2 reuse is enhanced hydrocarbon recovery which is usually associated with ER, and involves the injection of CO_2 into a depleted oil- or gas-bearing field to increase production. However, enhanced hydrocarbon recovery could also involve injecting CO_2 into clastic, carbonate, coal, or organic shale formations. DOE/NETL research focuses on maximizing the amount of CO_2 that could be stored,

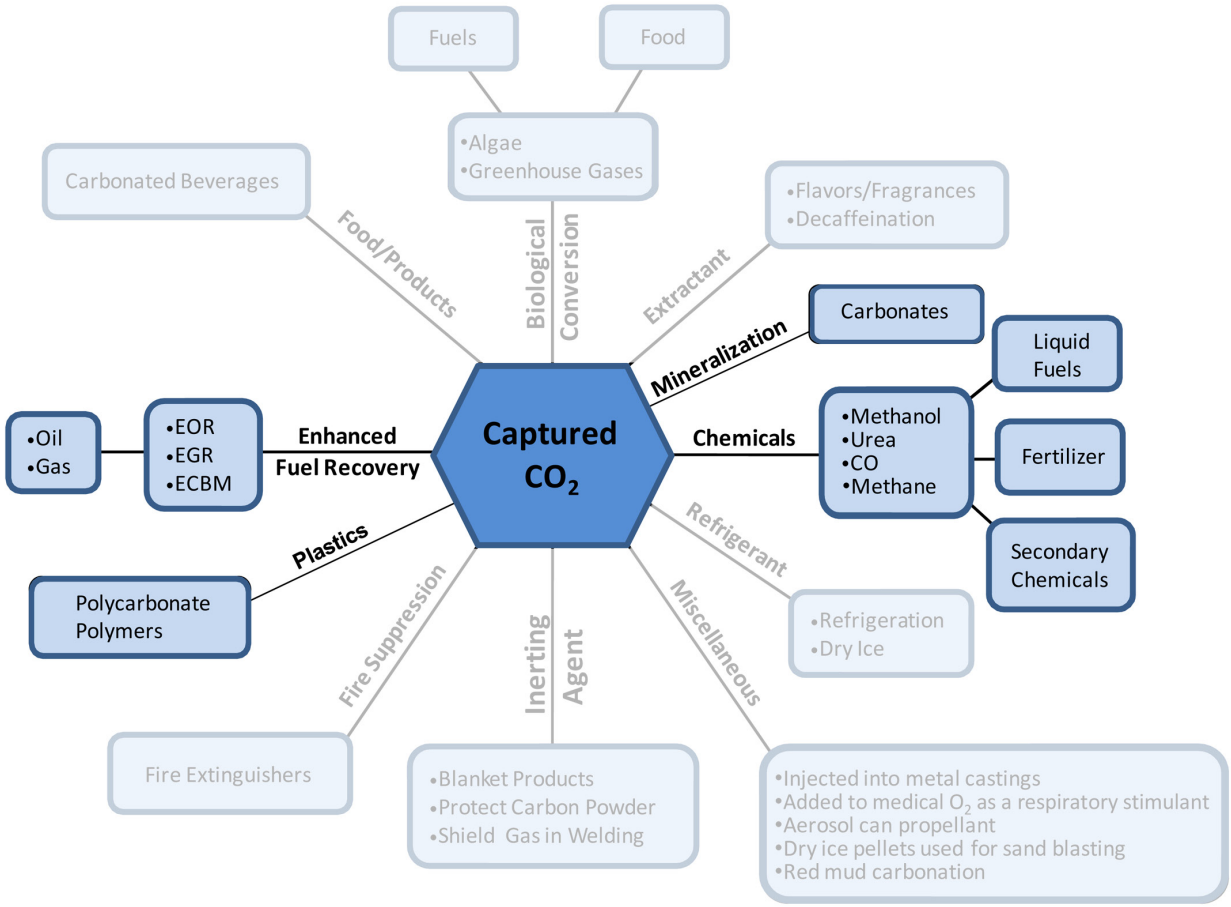


Figure 7: Illustrating the Uses of CO_2

CO_2 Reuse Goals

CO_2 Reuse covers a broad area of research with different technical challenges. The goals of the Carbon Storage Program are set to achieve successful implementation of various applications at different time horizons.

In general, the area of CO_2 reuse for carbon storage, with the exception of ER 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 reuse, including the development of technologies capable of economically fixing CO_2 in stable products for indirect storage.

as well as maximizing hydrocarbon production as part of the ER operations. If successfully developed and implemented, CO_2-enhanced oil recovery (EOR) would mean additional jobs, economic activity, and additional revenues to Federal and state treasuries and other sectors through both the production of oil and development of the infrastructure necessary for safe, permanent geologic storage of CO_2 throughout the United States. In addition, CO_2-EOR could serve as a catalyst, or pathway, to help incentivize CCUS technology development and ultimately decrease costs associated with geologic storage.

Processes or concepts must take into account the life cycle of the process to ensure that additional CO_2 is not produced beyond what is already being removed from or emitted into the atmosphere. Furthermore, while the utilization of CO_2 has some potential to reduce greenhouse gas emissions to the atmosphere, CO_2 has certain disadvantages as a chemical reactant. Carbon dioxide is rather inert and non-reactive. This inertness is the reason why CO_2 has broad industrial and technical applications. Each potential use of CO_2 has an energy requirement that needs to be determined; and the CO_2 produced to create the energy for the specific utilization process must not exceed the CO_2 utilized.

Infrastructure

The Infrastructure element of DOE's Carbon Storage Program is focused on R&D initiatives to advance geologic CO_2 storage toward commercialization. DOE determined early in the program's development that addressing CO_2 mitigation on a regional level is the most effective way to address differences in geology, climate, population density, infrastructure, and socioeconomic development. This element includes the following efforts designed to support the development of regional infrastructure for CCUS: the RCSPs, Geologic Site Characterization, Small-Scale Field Testing, Large-Scale Field Testing, and Knowledge Sharing.

As of the publication of this document, approximately 3.6 million tons of CO_2 have been stored in various geologic formations via the large-scale field tests being developed by the RCSPs.

The RCSP Initiative established the characterization of CCUS resources throughout the United States and portions of Canada that are being further enhanced by additional small- and large-scale CO_2 injection projects designed to address specific applied research related to progressing both geologic and terrestrial storage. In addition, the RCSPs began studying possible regulations and infrastructure requirements that would be needed should CCUS be deployed on a commercial basis. The seven RCSPs are focused on CCUS opportunities within their specific regions of the United States and portions of Canada.

DOE Water Use/Conservation Efforts Related to CCS

Water is involved in every step of the CCS process, from the industrial sources where CO_2 is generated to long after the CO_2 is injected into the ground. Water is heavily relied upon for cooling, especially in power generation facilities, and is also needed for other processes, including the regeneration of solvents used during CO_2 capture. The additional water load required for CCS may place a heavy demand on water resources in water-stressed areas.

The water issues associated with CCS revolve primarily around water usage at CO_2 sources and water extraction at CO_2 storage sites. On the storage side, impacts of CO_2 storage in appropriately targeted rock formations are expected to be minimal. CCS activities require great depth, and in most cases, the targeted formations will be separated from potable water resources by hundreds to thousands of feet of rock, including multiple low-permeability barriers. Extracting water from these storage formations is not necessary for carbon storage in most cases, though it may be beneficial in site-specific circumstances to remove water for treatment and beneficial reuse, pressure management, and CO_2 plume management.

DOE/NETL is actively addressing issues and opportunities in this area. As one example, the Water Working Group (WWG) was formed within the RCSPs to address stakeholder concerns regarding CCS and its potential interactions with water resources. The RCSPs are actively working on testing the various phases of CCS to identify safe, efficient, stable, and cost-effective methodologies to minimize impacts to the surrounding environment, both aboveground and belowground. State and federal regulations currently exist or are being developed to further ensure that CCS activities will be conducted in a responsible manner.

In another example, Argonne National Laboratory (ANL) is examining the extraction and reuse of formation water produced from CCS operations. The project investigates options for managing water removed from geologic formations, the costs of those options, and the potential for beneficial use of the water.

More information on DOE's water use/conservation efforts related to CO_2 capture is available onthe Water-Energy Interface webpage.

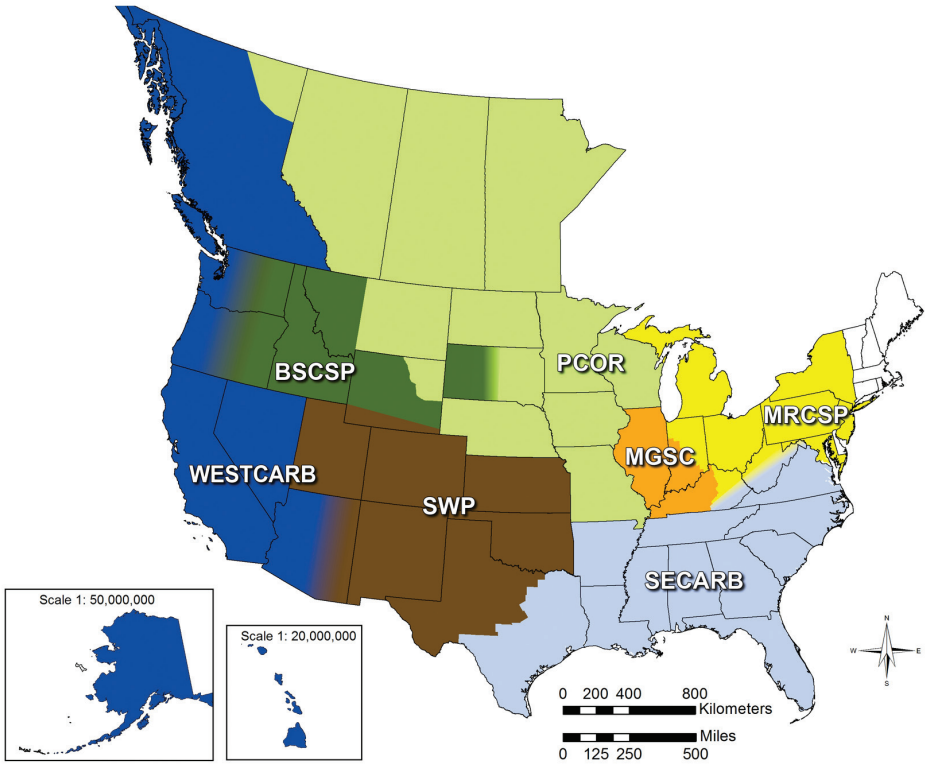


Figure 8: Regional Carbon Sequestration Partnership Regions

The **RCSPs** are responsible for developing a regional framework to enhance the development of new technologies and benefits, including human capital, stakeholder networking, regulatory and policy development, visualization knowledge centers, BPMs, and public outreach and education.

More information about each RCSP can be found at:

- **Big Sky Carbon Sequestration Partnership** (BSCSP) **Plains CO_2 Reduction (PCOR) Partnership**
- **Midwest Geological Sequestration Consortium** (MGSC)
- **Midwest Regional Carbon Sequestration Partnership** (MRCSP)
- **Southeast Regional Carbon Sequestration Partnership** (SECARB)
- **Southwest Regional Partnership on Carbon Sequestration** (SWP)
- **West Coast Regional Carbon Sequestration Partnership** (WESTCARB)

In collaboration with its partners in the Regional University Alliance, NETL's ORD is working to maintain and enhance the large amount of geospatial data and information collected throughout the RCSP sites and Core R&D Program. The benefit is that both the public and researchers will gain access to research results from ongoing projects throughout the United States.

DOE's Geologic Site Characterization efforts aim to characterize storage formations and reduce uncertainty associated with resource estimates in North America. Additional efforts include developing the necessary framework through identification of necessary regulations, stationary CO_2 sources, and any existing infrastructure to validate and deploy carbon storage technologies. Much of this information is available in NATCARB.

Although the RCSPs have largely completed their characterization efforts, several new characterization projects have been selected to evaluate high priority value-added reservoirs that can support the deployment of CCUS technologies. These efforts will include evaluation of the economics of developing a formation for storage and refining the technical methodology used to assess regionally important formations and ranking these formations for industry to consider for development. The additional efforts will build upon the data that was previously collected by the RCSPs and work with industry and the state geologic surveys to collect additional data on key formations through piggyback drilling operations and mining data that was not previously available. The work will also focus on the opportunities in all value added formations, including the integration of enhanced oil, gas, and geothermal energy that could be realized through the injection of CO_2 during storage operations.

The Recovery Act provided funding for two efforts that complement the existing Carbon Storage 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 approximately $1 million each through 2012 to support the development of professional training classes and academic curricula for scientists, engineers, lawyers, business professionals, and other individuals involved in CCS project development. The site characterization projects were awarded approximately $100 million to characterize high priority geologic storage formations that have the potential for future commercial-scale storage projects.

Small-Scale Field Testing (RCSP Validation Phase) – The RCSPs applied the knowledge and results of Characterization Phase activities to identify promising opportunities for CCUS in their respective regions during the Validation Phase. As a result, 19 geologic field tests and 11 terrestrial field tests were conducted. As of early 2012, the RCSPs were winding down their field project activities for the Validation Phase. However, the RCSPs are continuing their efforts to characterize their regional geologic CO_2 storage opportunities by using the results of the field projects and collecting additional data on storage formations. The RCSPs are applying lessons learned from work at these geologic sites to Development Phase activities.

The program recently awarded three small-scale injection projects to validate storage and injection into classes of geologic formations not previously tested. These and future small-scale field tests will be injecting CO_2 into saline formations, oil bearing reservoirs, and coal seams. Additional small-scale field tests will be necessary to complete the testing of storage in other high priority and unconventional formation. Understanding the impacts of different depositional systems on CO_2 flow, injectivity, containment, and resource are critical to the wide-scale deployment of CCUS throughout the United States. This can only be accomplished by testing and monitoring CO_2 in field tests, which help to validate simulation models and determine the effectiveness of the technologies needed to monitor CO_2 in the storage formations. Additional near-term tests will focus on value added storage reservoirs, such as depleted oil and gas fields where enhanced recovery associated with CO_2 storage could help support the deployment of commercial projects.

Large-Scale Field Testing (RCSP Development Phase) – DOE has been planning to conduct large-scale field testing of CO_2 injection into geologic formations since 2003, the initial year of the RCSP effort. Development Phase project development is based upon the information generated in the Characterization and Validation Phases, which has provided a significant body of scientific knowledge regarding CO_2 injection into geologic formations. Thus, the work to be conducted in the Development Phase is a logical continuation of earlier efforts. The large-scale field tests 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, and to achieve cost-effective integration with power plants and other large emission sources for capture. The RCSPs will place emphasis on MVA protocols and risk assessment frameworks that will provide detailed information on the dynamics of the systems being studied.

The Development Phase field tests will be implemented in three stages that will follow a sequential set of project steps:

- Site selection, characterization, National Environmental Policy Act (NEPA) compliance, permitting, and infrastructure development.
- CO_2 injection and monitoring operations.
- Site closure and post-injection monitoring.

Tests during the Development Phase involve the injection of 1 million tons or more of CO_2 into a variety of geologic formations. Each formation is considered a major storage reservoir in its RCSP region. These formations are expected to have the potential to store hundreds of years of stationary source CO_2 emissions. Results obtained from these efforts will provide the foundation for commercialization efforts for future, large-scale CCUS field tests across North America and will address future challenges associated with public acceptance, infrastructure (pipelines, compressor stations, etc.), and an acceptable regulatory framework. During the Development Phase, the RCSPs will strive to produce technical results to validate that CCUS can be conducted at commercial scale. To this end, the RCSPs aim to achieve a number of key goals during the Development Phase that relate to the lifecycle

The following Best Practices Manuals are available on the Carbon Sequestration Reference Shelf:

- Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations
- Public Outreach and Education for Carbon Storage Projects
- Site Screening, Selection, and Initial Characterization for Storage of CO_2 in Deep Geologic Formations
- Risk Analysis and Simulation for Geologic Storage of CO_2
  - Regional Carbon Sequestration Partnerships' Simulation & Risk Assessment Case Histories
- Geologic Storage Formation Classifications
- Terrestrial Sequestration of Carbon Dioxide
- Carbon Storage Systems and Well Management Activities

of their projects. Attainment of these goals is not an end product of the Development Phase, but instead will be achieved during all project phases including site selection, site characterization, permitting, CO_2 procurement, transportation, injection operations, monitoring, modeling, site closure, and post-closure monitoring and assessment.

Additional large-scale field tests are planned for the program to target high priority reservoir classes to demonstrate that CO_2 can be monitored and stored in value added formations throughout the United States. The projects will focus on storing CO_2 in depleted oil and gas fields while simultaneously enhancing production which could offset the economic cost of the field operations. The lessons learned from these projects will help understand the potential benefits of using the existing oil and gas infrastructure for long-term storage of CO_2. These field projects will also address very unique issues, such as how to mitigate the release of CO_2 from the thousands of existing wells, the benefits of fluid management, the challenges of monitoring multiple fluids, and the ability to simulate production and injection operations for CO_2 storage.

DOE's Knowledge Sharing is related to the development of human capital, stakeholder networking, best practice manual development, carbon mitigation plans, and public outreach and education throughout the United States.

Global Collaborations

The Global Collaborations Element includes ongoing partnerships with numerous global organizations to leverage U.S. expertise with other organizations that are conducting large-scale projects. These include organizations that are conducting demonstration projects, the CSLF, CERC, and NACAP. Supporting these projects directly benefits U.S. efforts to develop technologies and tools to meet the strategic goals of the Carbon Storage Program. In addition, these collaborations also provide a means to encourage transfer of lessons learned and knowledge sharing 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 CCUS industry throughout the world.

Assessment of Recent Carbon Storage Program Accomplishments

The RCSPs serve as the primary vehicle for promoting the development and deployment of CCUS technologies developed within the Core R&D element. The efforts of the RCSP small- and large-scale field test program include: (1) validating that storage resource and injectivity are present in regionally significant geologic formations to scaleup for commercial projects; (2) verifying that CO_2 will be contained in the target formations and not impact underground sources of drinking water (USDWs) and/or be released to the atmosphere; (3) determining the extent of the CO_2 plume underground and effects of pressure; (4) developing mitigation strategies in the unlikely event of CO_2 release; (5) developing BPMs for several CCUS-related topics; (6) engaging the public; and (7) supporting the development of future CCUS regulations. The accomplishments cited in the remainder of this document show that the Carbon Storage Program is making meaningful progress that will result in a series of best management practices guidelines that will be helpful in the carrying out of commercial-scale CCUS projects.

In particular, the initiation of the RCSP Initiative's Development Phase brings the realization of the most promising carbon mitigation solution within reach. These large-scale projects are possible due to the leadership and vision of both private and public sector partners, which has led to successful outcomes of numerous Core R&D projects and the first two phases of the RCSP Initiative. The goal of the Development Phase is to demonstrate the large-volume injection of CO_2 at a significant scale. These demonstrations will exhibit how the deployment and eventual commercialization of such technologies can play a major role in a robust CO_2 mitigation strategy. Moreover, NETL's CCUS field projects are helping DOE to develop technologies, that when deployed commercially, are capable of capturing 90 percent of CO_2 emissions with 99 percent storage permanence and less than 10 percent increase in the cost of energy.

Furthermore, the successful commercialization of CCUS technologies will not only allow the United States to continue to use fossil fuels in an environmentally responsible manner but, when coupled with the enhanced recovery of resources, these technologies will also provide an opportunity for greater recovery of domestic oil, natural gas, and coalbed methane (CBM).

The Carbon Storage Program was peer reviewed in 2008 and again in 2011 by a panel of international experts organized by the International Energy Agency Greenhouse Gas Program (IEA GHG). The first expert review panel found that the Development Phase of the RCSPs was an "excellent program that will achieve significant results for development of CCUS in the United States, Canada, and internationally." It was unanimously agreed that this phase of the RCSP Program will significantly advance and accelerate the field of CCUS. The review continued: "The individual projects within the Development Phase complement each other and together build a comprehensive and expansive research program, the size and scope of which is unique throughout the world. It was considered that all the individual projects would achieve the goals set of the overall program as set by NETL. The research standard of the projects was exemplary in most cases."

The second expert review panel in 2011 unanimously concluded that the RCSP Initiative continues to be a "world leading program for CO_2 storage research and public outreach." Panelists also recognized the strong research components of the Phase III projects, and they indicated that DOE/NETL has developed considerable expertise in site selection and management and dissemination of results. The reviewers were pleased with the "recent injection at Cranfield (SECARB) and indicated that the imminent injection at Decatur, Illinois, (MGSC) will further raise the international profile of the RCSP." They further concluded that the "Decatur site in Illinois could be used as a flagship project, and a benchmark for other Phase III projects." Another peer review by the American Society of Mechanical Engineers (ASME) in 2010 reached similar conclusions. For example, the panel applauded both the impressive fundamental science being conducted and the ability of the laboratories to collaborate and, in some cases, integrate their efforts. In particular, the panel was complimentary of those projects which sought to continue benchmarking work and fill knowledge gaps, providing widely accessed reports for existing and new technology implementation. More information on independent peer reviews of NETL's technology programs is available at: http://www.netl.doe.gov/technologies/coalpower/peer-review/.

The Carbon Storage Program has achieved numerous accomplishments through the growth, expansion, and introduction of new concepts and opportunities as a result of an adapting effort that incorporates novel activities to resolve issues uncovered by R&D activities and social demands. In the remainder of this document, significant accomplishments are reported for each aspect of the Carbon Storage Program. These accomplishments are identified for the 2010 and 2011 calendar years and organized in reverse chronological order by Carbon Storage Program element (Core R&D, Infrastructure, and Global Collaborations).

Core R&D Accomplishments

The Core R&D element contains four focal areas for applied research and carbon storage technology development: (1) Geologic Storage; (2) MVA; (3) Simulation and Risk Assessment; and (4) CO_2 Reuse. Core R&D is driven by technology needs and is accomplished through laboratory- and pilot-scale research aimed at developing new technologies and new systems for GHG mitigation.

Geologic Storage

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 11 major types of geologic storage reservoir classes, each having their own unique opportunities and challenges. For additional information, please see DOE's "Best Practices for Geologic Storage Formation Classification: *Understanding Its Importance and Impacts on CCS Opportunities in the United States*."

Geologic Storage Accomplishments

DOE Methodology for Assessing Geologic Storage Potential Published (2011). NETL scientists co-authored a detailed description of the DOE methodology for estimating CO_2 storage potential for oil and gas reservoirs, saline formations, and unmineable coal seams for the publication, titled, "*International Journal of Greenhouse Gas Control*." A summary version is contained in the 2010 Carbon Sequestration Atlas of the United States and Canada (Atlas III). The methodology is intended to produce high-level CO_2 resource estimates of geologic storage potential at regional and national scales. The methodology will be continuously refined, incorporating results of the Development Phase projects conducted by the RCSPs from 2008 to 2018.

Study of Offshore Geologic Storage Potential Publicized by American Association of Petroleum Geologists (2010). An article in the September 2010 issue of *The Explorer* describes a first-of-a-kind study to investigate the potential for underground storage of CO_2 in offshore U.S. geologic formations. Launched in cooperation with NETL by researchers at the Texas Bureau of Economic Geology, the project is evaluating new and historic data to identify at least one injection site within an area of Texas offshore state lands that could be suitable for the safe and permanent storage of CO_2 from commercial CCS operations. Using a cable, researchers send high-energy sound waves into the shallow marine sediments. When they bounce back, the sound waves are converted into high-resolution images, much like a sonogram, to determine potential storage sites. Submerged state lands of the northern Gulf of Mexico offer geologic storage advantages, such as proximity to existing oil and gas infrastructure, available sources of industrial CO_2, reduced environmental risks to underground sources of drinking water (USDWs) (compared to storage beneath land onshore), and state land ownership extending 12 nautical miles offshore – compared to three miles for all other states except Florida.

NETL Method Measures Subsurface Water Interaction with Coal Utilization Byproduct (2010). Using strontium (Sr) isotopes, NETL scientists quantified the extent to which mine water interacts with coal utilization byproduct (CUB)-containing grout used in remediation at the inactive Omega Coal Mine in West Virginia. The grout consisted of 98 percent fluidized bed combustion ash and fly ash with two percent Portland cement. The ratio of Sr isotopes (87Sr/86Sr) in the mine water clearly distinguished discharges from grouted and non-grouted areas, whereas conventional chemical analysis could not. Based on results of the study, water that interacted with the grout received 30 to 40 percent of its Sr from the grout mixture, suggesting the grout is chemically eroding at a rate of approximately 0.04 percent per year. The same approach is now being used to study the interaction of subsurface CO_2-laden waters with geologic media at carbon storage sites. The February 2010 issue of the journal, "*Applied Geochemistry*," describes the study.

Monitoring, Verification, and Accounting

An MVA program is designed to confirm permanent storage of CO_2 in geologic formations through monitoring capabilities that are 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, abandoned, and monitoring wells are structurally sound and that CO_2 will remain within the injection formation. For additional information, please see DOE's "Best Practices for Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations."

Monitoring, Verification, and Accounting Accomplishments

Promising Space Geodesy Monitoring for CO_2 Storage Deployed to Texas Field Operations (2011). Working in cooperation with NETL, a research team from the University of Miami deployed solar-powered global positioning system stations on the surface and seismic detectors in shallow underground vaults to monitor CO_2 injection operations at the Hastings West EOR site approximately 30 miles south of Houston, Texas, where Denbury Resources Inc. plans to begin oil extraction in 2012. The team will integrate surface geochemical sensor data and InSAR satellite imagery with the geodetic and seismic data recorded over the year into a straightforward series of procedures and algorithms to assess the cost and efficacy of tracking the CO_2 with this innovative approach. Denbury Resources operators are placing a new $1 billion pipeline in service to transport natural CO_2 from the Jackson Dome in Mississippi to Hastings for injection to depths of about 5,000 to 6,000 feet. The integrated monitoring system has the potential to detect real-time changes—such as ground displacements and seismic velocity anomalies in the reservoir and overburden—attributable to the injection of commercial quantities of CO_2.

Montana State University Completes Controlled CO_2 Release Experiment at the Zero Emissions Research and Technology (ZERT) Test Facility (2011). The ZERT test facility, located adjacent to the Montana State University (MSU) campus in Bozeman, Montana, includes a set of perforated pipes buried six feet below ground level, which allow the controlled release of CO_2 into the subsurface. From July 18 to August 15, 2011, CO_2 was released into the subsurface at a rate of 0.15 metric tons per day. Researchers from five national labs, three universities, one company, and the U.S. Geological Survey (USGS) measured key parameters, including soil CO_2 flux and total carbon; soil gas concentration; soil moisture, temperature, and conductivity; ground water and head space gas chemistry; plant health; and atmospheric transport of CO_2. A variety of traditional and novel investigative tools and techniques were employed during these measurements, including soil accumulation chambers, laser-based differential absorption instruments, infrared radiometry, neutron scattering, hyperspectral imaging, perfluorocarbon tracers, frequency-modulated spectroscopy, and eddy covariance techniques. The validity and utility of the novel tools and techniques were assessed by comparing results with those of traditional approaches. Results of individual experiments are now being analyzed and published in professional journals

DOE-Sponsored Study Helps Advance Scientific Understanding of Potential CO_2 Storage Impacts (2010). A Duke University study, sponsored by DOE, confirmed earlier research showing that proper site selection and monitoring is essential for helping anticipate and mitigate possible risks. The report, titled "Potential Impacts of Leakage from Deep CO_2 Geosequestration on Overlying Freshwater Aquifers," presented the results of a year-long study in which researchers incubated core samples from a variety of freshwater formations with CO_2 for more than 300 days. This work confirms earlier research conducted by NETL, several other DOE national laboratories, USGS, and others indicating that CCS sites must be carefully selected and monitored. The Duke researchers also identified three elements—manganese, iron, and calcium—which they suggest should be monitored, along with pH, as geochemical markers of CO_2 releases. The Duke research project is one of many sponsored by DOE to investigate the impact of CO_2 injection into geologic formations, including the

dissolution of metals from rock. This issue has been recognized for many years as a potential risk in CCS projects and it continues to be a focus of research. The research provides fundamental data that are used to improve risk assessment models and the design of CCS projects and monitoring programs. The risk to drinking water supplies can be mitigated by proper site characterization, the presence of an impervious caprock, and proper construction materials, and by maintaining proper operating conditions as required by EPA's Underground Injection Control Program.

NETL's Seismic Surveys Track CO_2 Movement Underground (2010). NETL researchers and collaborators at the University of Pittsburgh developed a correlation between acoustic wave velocity and relative CO_2 saturation that can be used to calibrate and refine the interpretation of 3-D seismic reflection surveys. Discussed in a special section on CO_2 storage in the journal, "*The Leading Edge*," the lab-scale study, conducted with actual reservoir rocks, shows the procedure could be employed to effectively track the movements of CO_2 after injection for carbon storage applications.

NETL Tracers Track Subsurface Movement of CO_2 at Storage Site (2010). Perfluorocarbon-based tracers developed at NETL and utilized by the RCSPs successfully detected underground migration of CO_2 at the San Juan Basin pilot storage test site in northern New Mexico. Tracer measurements provided the first evidence of subsurface migration of the plume, while traditional monitoring techniques for CO_2 at the wells simultaneously did not detect the migration. The tracers, measurable at concentrations of parts-per quadrillion and able to differentiate injected CO_2 from natural CO_2, were detected first in gas from the eastern-most of three production wells, peaking in February 2009, and then at the southwest production well in June 2009.

Simulation and Risk Assessment

The Simulation and Risk Assessment Focus Area is an integrated effort to develop advanced simulation models of the subsurface and to integrate the results into a risk assessment that includes both technical and programmatic risks. As the simulation models are refined with new data, the uncertainty surrounding the identified risks decreases, which in turn provides a more accurate risk assessment and mitigation plan for each project site.

Simulation and Risk Assessment Accomplishments

NETL Successfully Simulates Coal Seam Carbon Storage (2010). NETL developed a new model to determine the geologic and mechanical responses of coal-seam systems to CO_2 storage. The new model has improved the ability of simulating coal permeability so it agrees with field data obtained from the Allison field in northwest New Mexico – the site of the world's first enhanced coalbed methane-carbon storage field project. In addition to permeability, the model yields a better description of the roles of coal shrinkage and swelling, coal's elastic properties, and porosity of fractures in the coal seam. The simulation also provides better estimates for geophysical parameters that are difficult to measure in the laboratory. Results of the study appear in a special section on CO_2 storage in the journal, "*The Leading Edge*."

CO_2 Reuse

Carbon dioxide utilization efforts focus on pathways and novel approaches for reducing CO_2 emissions by developing beneficial uses for the CO_2. Carbon dioxide can be used in applications that could generate significant benefits. It is possible to develop alternatives that can use captured CO_2 for ER or enhanced gas recovery (EGR), or convert it to useful products such chemicals, cements, or plastics.

CO_2 Reuse Accomplishments

NETL Paper on CO_2 Reuse Photocatalysts Among Most Popular (2010). A paper authored by NETL scientists for the American Chemical Society publication, "*The Journal of Physical Chemistry Letters*," was recognized as one of the top 10 most accessed journal articles in 2010, illustrating the science community's interest in NETL's development of new CO_2 utilization technologies. The paper describes the synthesis and characterization of a new photocatalyst and its ability to convert CO_2 into value-added fuels and chemicals such as methanol and methane. The catalyst is activated by visible light, which comprises the majority of the sunlight available at the Earth's surface. Previous photocatalysts for this application were activated by ultraviolet light that makes up only one to five percent of light reaching the surface. Visible light activation will thus increase the efficiency of the catalytic process – an advance of paramount importance for CO_2 reuse applications.

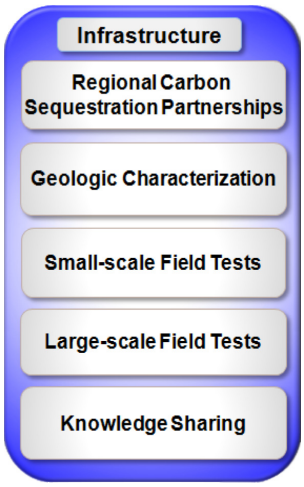
NETL Polymer Synthesis Laboratory Focuses on Materials for CO_2 Capture and Conversion (2010). NETL researchers are utilizing a new facility to develop synthetic methods to explore physical and chemical attributes of functionalized materials and their interactions with CO_2. Polymer Synthesis Laboratory (PSL) scientists are collaborating closely with molecular modelers to develop CO_2 capture devices in an "atoms up" approach that creates materials tailored specifically for the application. For example, synthetic polymer chemists are working with membrane fabrication experts to improve support materials for the preparation of supported ionic liquid (IL) membranes. PSL work will be a fundamental component of the planned collaboration between NETL and the Berkeley Energy Frontier Research Center (EFRC), one of 46 DOE-supported EFRCs partially funded through Recovery Act to address the full range of energy research challenges in renewable and carbon-neutral energy, energy efficiency, energy storage, and crosscutting science.

Novel Carbon Capture Process Would Utilize Industrial Waste Streams (2009). Preliminary results obtained at NETL show that the CO_2-bearing resource of reactive mixtures of acidic oil- and gas-field wastewater brines with caustic industrial byproducts high in calcium and magnesium content (e.g., flue gas desulfurization [FGD] spray dryer ash, Class C fly ash sub-bituminous coal combustion byproduct, bauxite residue slurry from the alumina-production process) could help reduce CO_2 while neutralizing caustic industrial waste for safe storage. Details of the study appear in the publication, "*Environmental Engineering Science*."

Novel NETL Photocatalyst Converts CO_2 for Reuse (2009). NETL scientists developed a heterostructured photocatalyst believed to be the first one capable of using the visible light (low-energy) portion of the electromagnetic spectrum for converting CO_2 and water (H_2O) into CH_4, methanol, and other value-added chemicals. The NETL material combines titanium dioxide (TiO_2) with cadmium-selenide (CdSe) quantum dot nanocrystals that absorb visible light photons, creating the excited electrons to initiate the photocatalytic reduction of CO_2. Photoactivity can be systematically tuned to utilize different regions of the electromagnetic spectrum just by changing the size of the CdSe nanocrystal photosensitizer. This significant advance in the development of new technologies for CO_2 capture and reuse is detailed in the inaugural issue of American Chemical Society's "*Journal of Physical Chemistry Letters*."

Infrastructure Accomplishments

The Infrastructure Element of DOE's Carbon Storage Program is focused on R&D initiatives to advance geologic CO_2 storage toward commercialization. DOE determined early in the program's development that addressing CO_2 mitigation on a regional level is the most effective way to address differences in geology, climate, population density, infrastructure, and socioeconomic development. This element includes the following efforts designed to support the development of regional infrastructure for CCUS: the RCSPs, geologic characterization, small- and large-scale field tests, and knowledge sharing.



Regional Carbon Sequestration Partnerships

The seven RCSPs are determining the best geologic and terrestrial storage approaches to safely and permanently store CO_2 for their specific regions. Geographical differences in fossil fuel use and storage opportunities across North America dictate regional approaches to storage of CO_2 and other GHGs. The seven RCSPs focus on the CCUS 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 CCUS commercialization within their respective regions. Although terrestrial sequestration is no longer a focus of the program, the RCSPs have done considerable work in this area.

All RCSP accomplishments are indicated by the respective partnership logo and can be found under the small- and large-scale field tests section, which is located after the Geologic Characterization accomplishments (see page XX).

Geologic Characterization

The process of identifying suitable sites with adequate storage potential involves methodical and careful analysis of the features of promising geologic formations. While geologic formations are infinitely variable in detail, they are classified by geologists and engineers by their trapping mechanism, hydrodynamic conditions, lithology, and depositional environment. The depositional environment, or the conditions under which sediment was deposited over many years, influences how formation fluids are held in place, how they move, and how they interact with other formation fluids and solids (minerals). Certain geologic properties may be more favorable to the long-term containment of CO_2. The efforts of DOE's RCSPs, other large- and small-scale CO_2 injection projects, the ARRA Site Characterization projects, and NATCARB have substantially increased the knowledge base regarding the potential to use different geologic formations not previously studied in detail for use in geologic storage of CO_2.

Geologic Characterization Accomplishments

Recovery Act Project Reports Successful Gorgas Power Plant Well to Target Carbon Storage (2011). A characterization well drilled 4,915 feet beneath Alabama Power Company's William C. Gorgas coal-fired power plant (1,400 megawatts [MW]) in Parrish, Alabama, encountered promising formations for carbon storage with these strata also bounded by competent seals. Extensive borehole data collected including geophysical well logs, core, and seismic tests will be used to determine the extent of stacked storage in the units underlying the Gorgas Plant. Hydrocarbon shows were also present in the well at the Fayette sandstone (1,060 feet), the Boyles Sandstone (2,027 feet), and the Hartselle Sandstone (from 2,622 to 2,716 feet). A project team led by University of Alabama researchers

is studying these data from the well in cooperation with NETL to more accurately quantify the resource of Black Warrior Basin saline formations and mature hydrocarbon reservoirs for commercial carbon storage and possible enhanced oil and gas recovery.

First Extended-Reach Test Bore Completed in Kansas Arbuckle Formation (2011). Working in cooperation with NETL, a project team, organized by the University of Kansas Center for Research, with industry partner Murfin/Vess Drilling Company, completed collecting geologic, geophysical, and geochemical data from a horizontal test well bored approximately 5,800 feet deep into the top of the Arbuckle formation. Data from the well will be used to confirm the presence of paleokarst features, predicted from volumetric curvature seismic analysis performed earlier in the project. In addition, the data will improve the accuracy of numerical models in simulating plume migration and estimating CO_2 storage resource, and could be utilized by future CCS projects in Kansas and other states. The Arbuckle formation was selected based on its geologic setting, geologic properties, and proximity to some of the state's largest oil and gas producers.

Sandia Technologies Completes Characterization Well (2011). Sandia Technologies LLC, in coordination with team members Conrad Geoscience, Schlumberger, Columbia University, Rutgers University, the New York State Museum, and the Lawrence Berkley National Laboratory (LBNL), completed deep test well drilling of the Newark Basin. This test well produced a continuous stratigraphic section of the Newark Basin to a depth of 6,885 feet, the deepest continuous boring in the Basin. Coring and well logging results provided important data related to formation fluid samples; formation pressures; and estimates of formation porosity, permeability, grain and bulk density, lithology, and mineralogy. Researchers are currently analyzing hydrologic, geologic, and oil and gas well data; creating geologic and conceptual models; and integrating the data into a national database. This NETL-supported project is designed to characterize the northern tier of the basin and to provide valuable insights and a better understanding of the basin's ultimate storage resource.

Stratigraphic Test Well Completed in Southwest Wyoming to Characterize Geologic Formations for Potential CO_2 Storage (2011). A project team, organized by the University of Wyoming with industry partner Baker Hughes, completed installation of a stratigraphic test well 12,810 feet into the Rock Springs Uplift, and collected attendant geologic, geophysical, and geochemical data and samples. The key targeted storage formations in the Rock Springs Uplift are the Weber/Tensleep sandstone and the Madison Limestone at depths of approximately 11,500 feet and 12,500 feet, respectively. The overlying Dinwoody formation, at a depth of 10,600 to 10,800 feet, is expected to serve as the low-permeability capping/sealing unit that will prevent the stored CO_2 from migrating toward the surface and potentially contaminating overlying formations. Data collected from the well and other geophysical surveys will allow numerical simulations to yield more accurate predictions of CO_2 storage resources and potential plume migration and could be utilized to underpin future large-scale CCS projects in Wyoming. The Rock Springs Uplift was selected for characterization based on its geological setting and proximity to some of the state's largest sources of anthropogenic CO_2. The characterization well is located a few miles from the Jim Bridger coal-fired power station, which is the largest point-source of CO_2 in Wyoming. Preliminary analyses indicate that the Rock Springs Uplift could store 26 billion tons of CO_2—a resource sufficient to accept Wyoming's current annual CO_2 emissions of 55 Mt for more than 470 years.

The South Carolina Research Foundation Completed Collection, Processing, and Analysis of 240 Kilometers of 2-D Seismic Data Collected from the Buried South Georgia Rift (SGR) Basin (2011). The South Georgia Rift (SGR) Basin is a regional basin that extends across multiple states with limited subsurface information. Seismic information that was collected and analyzed is being used to determine if there are stratigraphic and structural controls within the project area to prevent injected supercritical CO_2 from potentially migrating upward into the Coastal Plain formations. The 2-D seismic data was evaluated and used to select the most promising location for the installation of a characterization boring. Recently, one square mile of 3-D seismic data was collected adjacent to the proposed boring location to confirm the suitability of the selected site.

The data from the 3-D survey is being tied back into the 2-D seismic survey. Multiple models have been developed using available historical data with the seismic data to determine the storage potential of the Jurassic and Triassic strata of the SGR Basin. The recipients have obtained access and started preparing the site for the installation of a characterization boring, scheduled for the second half of 2012. The geologic, geochemical, and geophysical data collected from the characterization boring will be used to update existing models and to help estimate the storage potential of the SGR Basin.

University of Illinois Site Characterization Accomplishments (2011). In an effort to evaluate the physical extent of the geologic formations of the Illinois Basin that show promise for storing CO_2, researchers at the Illinois State Geologic Survey and University of Illinois acquired 120 miles of 2-D seismic data across west-central Illinois. There is virtually no information on the subsurface in this part of Illinois, and the new data set will be used to more fully characterize the most important reservoirs of the Illinois Basin for storing CO_2, such as the Mt. Simon, St. Peters, and Petosi formations. A geologic profile will be developed from the data to evaluate the thickness and extent of the Ordovician and Cambrian strata, which, in turn, will be used to improve the CO_2 storage resource estimates for the Illinois Basin where industrial source emissions are estimated to be approximately 290 million metric tons of CO_2 per year.

WESTCARB's Activities Support CCS Development in Key Regions (2010-2011). A stratigraphic well drilled in the Sacramento Basin of California in 2011 is providing WESTCARB with data on CO_2 storage potential of regionally extensive geologic formations. Drilled to a vertical depth of 6,900 feet, the Citizen Green well is located in an historic natural gas-producing region in close proximity to major industrial and power plant CO_2 sources. Other WESTCARB research focused on characterizing formations in the Colorado Plateau and Basin and Range Provinces in Arizona to assess storage potential for the coal-fired power plants that are the largest point sources of CO_2 in the WESTCARB region. For California's fleet of natural gas combined cycle (NGCC) power plants, WESTCARB is providing engineering, economic and geologic assessments of CCS, including capture technology options for retrofits and new builds. WESTCARB also continued outreach efforts to inform California policymakers about CCS technology, including serving on the Technical Advisory Committee for the California Carbon Capture and Storage Review Panel and meeting with permitting and regulatory agencies tasked with incorporating CCS as a technology option for GHG emissions reduction compliance.

Terralog Technologies Completes Drilling of Site Characterization Well (2010). In May 2010, Terralog Technologies USA, Inc., completed drilling the first of two wells for characterization of the Pliocene and Miocene Formations in the Wilmington Graben formation. This project, titled, "Characterization of Pliocene and Miocene Formations in the Wilmington Graben, Offshore Los Angeles, for Large Scale Geologic Storage of CO_2" (DE-FE0001922), aims to: (1) improve evaluation and interpretation of existing 2-D and 3-D seismic data; (2) complete acquisition and interpretation of several additional 2-D seismic lines; (3) perform a detailed log evaluation of existing exploration wells in the area; (4) drill and core two new evaluation wells into the Graben (one from City of Los Angeles [CLA] Property and one from Port of Long Beach property); and (5) develop 3-D geologic models, geomechanical models, and CO_2 injection and migration models for the region. Terralog designed and located the CLA SFI#3 well for optimal data collection. This well was drilled from the Terminal Island Sanitation Plant in Los Angeles, California, to a total depth of approximately 5,500 feet with 1,000 feet lateral offset, giving an approximate total vertical depth of 4,500 feet.

New ARRA Funding Boosts Industrial CCS R&D (2010). Twenty-two projects were selected to receive funding from the Recovery Act to accelerate CCS R&D for industrial sources. The 22 projects, located in 15 states, have received more than $575 million in Recovery Act funds to support the goal of cost-effective CCS deployment within 10 years. The funding for the projects covers four areas of CCS R&D: (1) large-scale testing of advanced gasification technologies ($312 million); (2) advanced turbo-machinery to lower emissions from industrial sources ($123 million); (3) post-combustion CO_2 capture with increased efficiencies and decreased costs ($90 million); and (4) geologic storage site characterization ($50 million). The Carbon Storage Program received $10 million for

geological storage site characterization projects, and the remaining funding was allotted to the ICCS area. Successful projects related to this funding are listed below.

Factors Affecting Unconventional Oil Recovery from Rocky Mountain Region Evaluated (2010). UNDEERC researchers examined the key factors affecting oil production in the Bakken Formation—among the richest hydrocarbon source rocks in the world—to gain a clearer understanding of how to produce the vast resource underlying portions of Montana and North Dakota efficiently and consistent with environmental guidelines. The evaluation will guide further development of a web-driven Bakken decision support system with geographic information system (GIS) capability, geomechanical studies of middle Bakken cores relative to fracturing, and geochemical studies to understand variables that impact production. The work is part of the Joint Program for R&D for Fossil Energy-Related Research between NETL and UNDEERC.

Geologic Playbooks and Database of the Permian Basin Made Publicly Available (2009). In cooperation with NETL, researchers at the University of Texas at Austin produced the most up-to-date analysis available regarding geologic controls on reservoir development in the Permian Basin – the largest oil producing region in the United States. Cumulative oil production from the Permian Basin is more than 30 billion barrels of oil, with an estimated 30 billion barrels of mobile oil remaining. Fourteen selected reservoirs in the basin now have fully illustrated reports that include critical summaries of published literature integrated with new unpublished research conducted during the project. The data will decrease environmental risk, increase efficiency, and provide an important basis and incentive for new drilling.

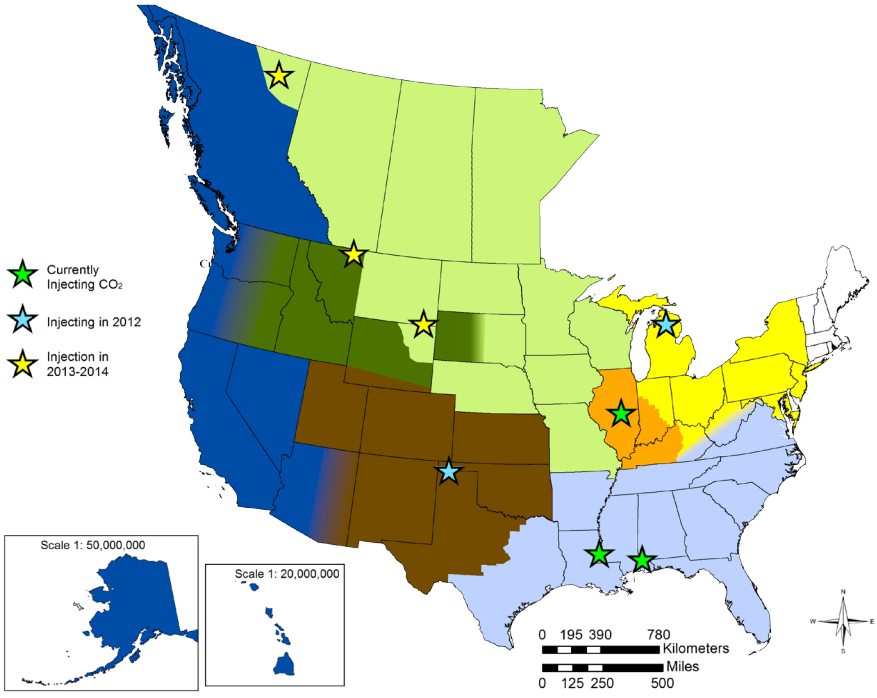


Figure 9: Map of Validation Phase CO_2 Storage Projects

Small-Scale Field Tests

DOE is supporting a number of small-scale field tests (injection of less than 500,000 metric tons of CO_2 per year) to explore various geologic CO_2 storage opportunities within the United States and portions of Canada. DOE's small-scale field test efforts are designed to demonstrate that regional reservoirs have the capability to store thousands of years of CO_2 emissions and provide the basis for larger volume, commercial-scale CO_2 tests. The field studies are focused on developing better understanding 11 major types of geologic storage reservoir classes, each having their own unique opportunities and challenges. Understanding these different storage classes provides insight into how the systems influence fluids flow within these systems today, and how CO_2 in geologic storage would be anticipated to flow in the future.

Small-Scale Field Tests Accomplishments

Field Projects Aim to Confirm CCS Security and Environmental Safety (2011). On July 6, 2011, DOE announced the selection of three small-scale CO_2 injection field projects to collectively receive $34.5 million over four years. The total award value of the projects, which aim to confirm that long-term geologic CO_2 storage is safe and environmentally secure, is more than $45 million, with approximately $10.5 million provided by the recipients. The three projects include: (1) Blackhorse Energy, LLC, which will inject approximately 53,000 tons of CO_2 into a geologic formation located in Livingston Parish, Louisiana, to assess the suitability of strandplain geologic formations for future large-scale geologic CO_2 storage in association with EOR; (2) the University of Kansas Center for Research, Inc. will inject at least 70,000 metric tons of CO_2 into multiple formations to demonstrate the application of state-of-the-art MVA tools and techniques to monitor and visualize the injected CO_2 plume and establish best practice methodologies for MVA and closure in shelf clastic and shelf carbonate geologic formations; and (3) the Virginia Polytechnic Institute and State University will attempt to reduce uncertainty, test the properties of coal seams, and evaluate the potential for ECBM recovery by injecting approximately 20,000 tons of CO_2 into unmineable coalbeds. The data from these projects will be incorporated into NATCARB.

Midwest Has Potential to Store Hundreds of Years of CO_2 Emissions (2011). Small-scale CO_2 injection field tests conducted by MRCSP indicate that their region has the geologic potential to store hundreds of years of regional CO_2 emissions primarily in deep saline formations. The MRCSP Phase II field tests included seven small-scale field validation tests: three geologic injection tests, one in each of the major geologic provinces of the region (the Michigan Basin, the Appalachian Basin, and the Cincinnati Arch) and four terrestrial field tests representative of the region's diversity (croplands, reclaimed minelands, reclaimed marshlands, and forested wetlands). The small-scale geologic field tests injected CO_2 into saline formations to validate data gathered in geological characterization research. The field tests also found that oil and gas reservoirs have a high potential for enhanced oil and gas recovery.

Field Tests Explore Potential for CO_2 Storage in Diverse Geologic and Terrestrial Sinks in the Big Sky Region (2010–2011). The world's first permit for CO_2 injection into a continental flood basalt formation was awarded to the Big Sky Carbon Sequestration Partnership (BSCSP) by the Washington Department of Ecology. Basalts represent a unique type of storage reservoir; although the basalt flows themselves have inherently low porosity and permeability, substantial CO_2 injectivity and storage capacity may exist in brecciated zones between the basalt layers. In this pilot-scale test, scheduled for late 2012, approximately 1,000 tons of supercritical CO_2 will be injected into a deep basalt formation near the town of Wallula in eastern Washington State. Extensive hydrologic tests have been completed in the 2,875-foot deep injection well to examine the potential for hydraulic communication between the targeted injection zone and overlying formations. BSCSP also completed an extensive geologic characterization and the first stage of a seismic survey of the Kevin Dome region in north-central Montana. A large-scale test will remove approximately 1,000,000 metric tons of naturally occurring CO_2 from the top of Kevin Dome and inject it into the downdip flanks of the dome's Duperow formation, where significant additional storage capacity is possible. Field tests were also completed to determine the potential for terrestrial storage in the region's croplands, rangelands, and forests.

Alabama Injection Project Aimed at EOR, Testing Important Geologic CO_2 Storage (2010). A DOE-funded CO_2-EOR project, led by the University of Alabama at Birmingham, was initiated in the Citronelle Field of Mobile County, Alabama. This "Anthropogenic Test" is the first RCSP project to utilize anthropogenic, or manmade, CO_2 for geologic storage. The results of the 30,000-ton CO_2 injection will provide estimates of oil yields from EOR and CO_2 storage resource in depleted oil reservoirs. The primary goal of the project is to demonstrate that remaining oil can be economically produced using CO_2-EOR technology in untested areas of the United States. The Citronelle Field appears to be an ideal site for concurrent CO_2 storage and EOR because it is composed of sandstone reservoirs in a simple structural dome and has preexisting infrastructure. Once the oil has been recovered, the remaining storage resource of the depleted oil reservoirs and saline formations in the Citronelle Dome is estimated to be in the range of 0.5 to 2 billion tons of CO_2.

PCOR Partnership Field Test Finds Potential for Permanent Storage of CO_2 in Lignite Seams (2010). The PCOR Partnership injected approximately 90 tons of CO_2 over two weeks into a 10- to 12-foot deep coal seam at an approximate depth of 1,100 feet in Burke County, North Dakota, in a DOE-sponsored field test. This demonstration shows that opportunities to permanently store CO_2 in unmineable coal seams of lignite may be more widespread than previously documented. The field test showed that the CO_2 did not significantly move from the wellbore and was contained within the coal seam for the duration of a three-month monitoring period. In addition, the PCOR Partnership evaluated a variety of carbon storage operating conditions to determine their applicability to similar coal seams, and investigated the feasibility of combining CO_2 storage with enhanced methane production. The results indicate that suitable lignite seams are potential targets for CO_2 storage, and that the combination of CO_2 storage and enhanced methane production has the potential to offer both a near-term economic return and a long-term environmental benefit. The successful injection and storage of CO_2 in this field test provides for similar CO_2 injection tests at a larger scale and longer duration.

PCOR Partnership Study Shows "Sour" Gas Streams Safe for Carbon Storage (2010). A field test completed by the PCOR Partnership produced results that show gas streams containing both CO_2 and hydrogen sulfide (H_2S) can be safely used for carbon storage. The findings of the PCOR Partnership's test also demonstrated that carbon storage using "sour" gas streams can be successfully combined with EOR and H_2S disposal. During the four-year field test, a gas stream (70 percent CO_2, 30 percent H_2S) was injected at a depth of 4,900 feet into the Zama oilfield in northwestern Alberta, Canada. Approximately 33,500 tons of sour gas was injected, simultaneously storing CO_2, disposing of H_2S, and increasing oil recovery. All of the project goals were achieved, including: demonstrating the safe and feasible capture and injection of a sour gas stream into properly characterized and selected underground reservoirs; designing, implementing, and demonstrating MVA strategies; and confirming that sour gas could be successfully used for EOR operations in a previously untested geologic feature.

SECARB Reaches Milestone (2010). More than 2.5 million metric tons of CO_2 has been injected at depths greater than 10,000 feet into the lower Tuscaloosa Formation near Natchez, Mississippi. Beginning with EOR operations conducted at the Cranfield site by Denbury Resources Inc., the SECARB project proceeded to demonstrate the feasibility of injecting CO_2 from a natural source into a regionally significant brine-bearing formation and the use of multiple tools to monitor the subsurface movement of the injected CO_2. The project is designed to determine whether the immediate commercial benefit of EOR can offset infrastructure development costs for follow-on, large volume, long-term storage of CO_2 in underlying saline formations.

SECARB Completes Phase II CO_2 Injections (2010). Injection operations for the Black Warrior Basin Coal Seam Project located near Tuscaloosa, Alabama, have concluded, representing the last SECARB Phase II injection to be completed. An existing coalbed methane (CBM) well was converted for the CO_2 injection, and three wells were drilled to monitor reservoir pressure, gas composition, and the CO_2 plume. A total of 277 tons of CO_2 were injected in coal seams of the Pratt, Mary Lee, and Black Creek Coal groups within the upper Pottsville Formation. The targeted seams range from 940 to 1,800 feet in depth and from six inches to six feet in thickness. Coal in the Black Warrior Basin – an area of about 23,000 square miles located in northwestern Alabama and northeastern Mississippi – has the potential to store 1.12 to 2.32 Gigatons of CO_2 (approximately the amount that Alabama coal-fired power plants emit in two decades), and CO_2-ECBM recovery could squeeze another 1.5 trillion cubic feet of natural gas from the reservoirs.

PCOR Partnership Successfully Demonstrates Terrestrial CO_2 Storage Practices in Great Plains Region of U.S. and Canada (2010). The PCOR Partnership successfully completed a field test demonstrating approaches for terrestrial CO_2 storage in North America. The field test was conducted in the Prairie Pothole Region – an area that stretches from central Iowa into Northern Alberta, Canada, and contains thousands of shallow wetlands formed by retreating glaciers approximately 10,000 years ago. Terrestrial storage involves removal of CO_2 by plants

from the atmosphere using photosynthesis and storing the GHG in biomass and soils. Soil and gas samples from restored grasslands, native prairie, croplands, and wetlands throughout Montana, North and South Dakota, Minnesota, and Iowa were collected by participating organizations. Carbon uptake and storage measurements were also measured to estimate the net change in GHG levels. The results will help to develop protocols for terrestrial carbon credit development and trading, as well as serve as a model for promoting and implementing terrestrial sequestration across the Prairie Pothole Region and other areas of North America.

PCOR Partnership Field Test Demonstrates Viability of Simultaneous CO_2 Storage and EOR in Carbonate Reservoirs (2010). The PCOR Partnership conducted a field test that demonstrated using CO_2 in an EOR method called "huff-and-puff" to assess the carbon storage potential of geologic formations. The PCOR Partnership collaborated with Eagle Operating, Inc. to complete the test in the Northwest McGregor Oil Field in Williams County, North Dakota. The "huff-and-puff" EOR method consists of three phases: injection, soaking, and production. During the test, 440 tons of liquid CO_2 were injected into a producing oil well in the Mission Canyon Formation, which is part of the Madison Group of Mississippian-age carbonate rocks in the western United States. The injection occurred at a depth of approximately 8,050 feet, at which CO_2 is miscible and blends with residual, in-place oil. Following two weeks of soaking, the well was placed back into operation and production more than doubled over the course of a three-month period. In addition, the test also determined that two technologies – a reservoir saturation tool (RST) and vertical seismic profiling (VSP) – have the potential to be effective tools for detecting and monitoring small-volume CO_2 plumes in deep carbonate reservoirs.

Award-Winning DOE Technology Scores Success in SWP's Carbon Storage Project (2010). SWP successfully demonstrated SEQURE™ tracer technology, which detects and tracks CO_2 movement in underground geologic storage reservoirs, at its San Juan Basin test site. Developed by NETL scientists, the technology uses perfluorocarbon tracers (PFTs) to provide a verifiable method to measure CO_2 movements and detect potential CO_2 migration. The tracer technology improved modeling techniques vital to defining storage resource, injection capability, flow rates, and numbers of wells associated with storage sites. Carbon dioxide concentrations as small as parts-per-quadrillion levels can be measured by the technology, and injected CO_2 can be differentiated from natural CO_2. SWP began injecting approximately 35,000 tons of CO_2 into the San Juan coalbed to maximize permanent storage of CO_2, while simultaneously recovering natural gas. The San Juan Basin, considered one of the top locations worldwide for CBM recovery and an ideal site for CO_2 storage, contains three CBM-producing wells and a central injection well.

The Interstate Oil and Gas Compact Commission (IOGCC) and the Regional Partnerships Meet to Discuss the Phase II Regulatory Lessons Learned (2010). The IOGCC hosted the RCSP Regulatory Working Group members in Santa Fe, New Mexico, on January 21-22, 2010, to discuss their Validation and Development Phase regulatory experience and the implications for future CO_2 storage projects. The seven RCSPs identified a broad range of regulatory issues that covered NEPA through the UIC permitting process. The regulatory issues or challenges identified by the RCSPs included regulatory infrastructure and systems, regulatory jurisdiction, cooperation and coordination among regulatory entities, and stakeholder buy-in. The IOGCC summarized the RCSP challenges and recommendations in a report, titled "IOGCC Task Force Biennial review of Legal and Regulatory Environment for the Storage of Carbon Dioxide in Geologic Structures."

DOE Targets Rural Indiana Geologic Formation for CO_2 Storage Field Test (2009). MGSC completed the injection of ~5,000 tons of CO_2 to evaluate the carbon storage potential and test the EOR potential of abandoned oil wells in the Mississippian-aged Clore Formation in Posey County, Indiana. The three-member project team, which is comprised of the Illinois State Geological Survey at the University of Illinois, the Indiana Geological Survey, and Gallagher Drilling, Inc., is injecting CO_2 into the Mumford Hills oilfield at an approximate depth of 1,900 feet.

MRCSP Completes Successful CO_2 Injection Test in the Mt. Simon Sandstone (2009). MRCSP successfully injected 1,000 metric tons of CO_2 into the lowest 100 feet of the Mt. Simon Sandstone (3,230 to 3,530 feet below ground) at Duke Energy's East Bend Generating Station in Boone County, Kentucky. Preliminary data indicated that the formation has good CO_2 storage potential and could possibly serve as a repository for captured CO_2 emissions. The formation is covered by layers of low permeability rock and possesses several properties that are conducive to CO_2 storage, such as the appropriate depth, thickness, porosity, and permeability. Prior to drilling the test well, MRCSP conducted a seismic survey at the site and obtained necessary permits for the injection test from EPA and the Kentucky Division of Oil and Gas. Following the permitting process, the researchers injected clean brine in order to determine formation properties like the maximum injection rate and then injected approximately 1,000 metric tons of CO_2 in two, 500-meter-ton steps. The injection rate, pressure, temperature, and quantity of CO_2 in the formation were measured throughout the test to confirm that the injection proceeded as planned. MRCSP researchers have monitored groundwater at the site for the last two years to ensure that it is unaffected by the injected CO_2. The Eau Clair Shale provides approximately 450 feet of containment above the injection zone.

Large-Scale Field Tests

DOE is supporting a number of large-scale (greater than 1 million metric tons CO_2 injected) field tests in different geologic storage formations to confirm that CO_2 capture, transportation, injection, and storage can be achieved safely, permanently, and economically over extended periods. Results from these tests will provide a more thorough understanding of CO_2 migration and permanent storage within various types of depositional systems and formation types. The storage formations being tested are considered regionally significant and have the potential to store hundreds of years of CO_2 stationary source emissions.

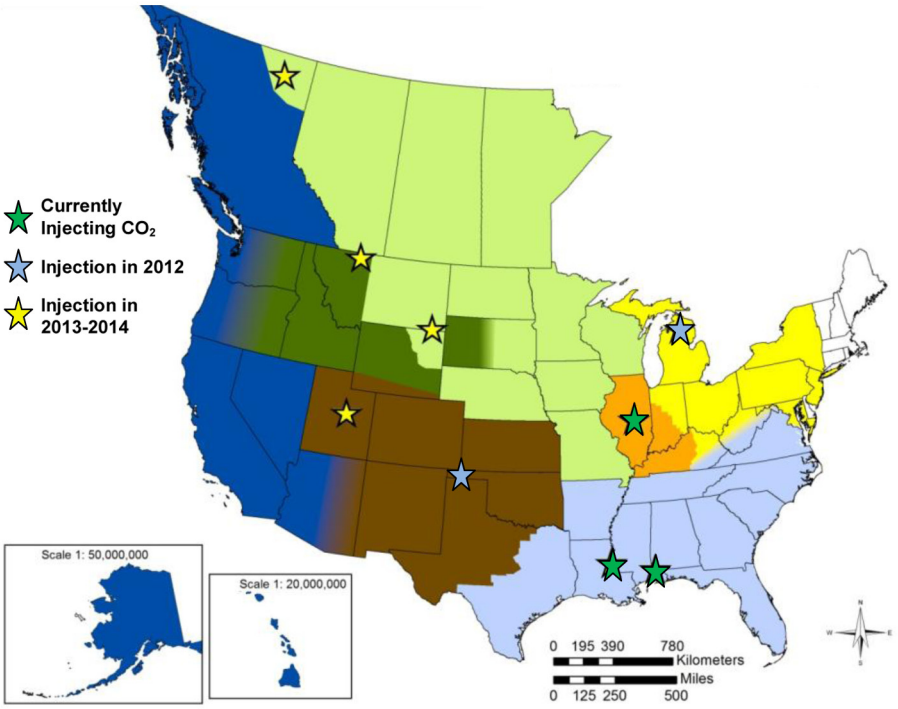


Figure 10: Map of Development Phase CO_2 Storage Projects

Large-Scale Field Tests Accomplishments

Preparations Completed for Drilling and Characterization of SECARB Anthropogenic Site (2011). The SECARB Anthropogenic Test R&D project is a demonstration of the deployment of CO_2 capture, transport, geologic storage, and monitoring technology. The capture component of the test takes place at Southern Company's James M. Barry Electric Generating Plant (Plant Barry) in Bucks, Alabama. The capture facility, equivalent to 25 MW, will utilize post-combustion amine capture technology licensed by Mitsubishi Heavy Industries America. Carbon dioxide captured at the plant will be compressed and transported 12 miles by pipeline for underground storage in a deep saline geologic formation within the Citronelle Dome located in Citronelle, Alabama.

On January 31, 2011, the geologic characterization well (D9-8#2) was completed to 11,817 feet to determine the physical and chemical characteristics of the Paluxy Formation, which is the target saline formation for the Anthropogenic Test project. Reservoir data gathered from this well were used to refine the geologic model, reservoir, and simulation and injection operations.

On March 18, 2011, a Finding of No Significant Impact (FONSI) was signed following the "Final Environmental Assessment for the Southeast Regional Carbon Sequestration Partnership (SECARB) Phase III Anthropogenic Test Project" (DOE/EA-1785D). Based on the analyses in the Environmental Assessment (EA), DOE determined that its Proposed Action, awarding a Federal grant to SECARB to inject approximately 150,000 metric tons of CO_2 per year for two years into a deep saline aquifer, would result in no significant adverse impacts.

On November 22, 2011, ADEM issued two UIC Class V injection well permits to Denbury Resources, LLC, for injection wells D9-7#2 and D9-9#2 at Citronelle Oil Field, located north of Mobile, Alabama. ADEM modified the draft permit to include additional details that were requested by EPA following a 30-day review of the permit application. The injection wells are an integral part of the Phase III Anthropogenic Test being conducted by DOE, through SECARB (DE-FC26-05NT42590), to test the

The following efforts are funded outside of the Carbon Storage Program and complement existing activities to commercialize geological storage-related technologies:

The **Carbon Capture and Storage Initiative (CCSI)** is led by NETL and leverages the core strengths of DOE's national laboratories in modeling and simulation. CCSI's goal is to deliver a set of tools that can simulate scale-up of a broad suite of new CCS technologies, from laboratory to commercial scale. The first five years of the project will focus on developing capabilities applicable to oxy- and post-combustion capture by solid sorbents and advanced solvents. Among possible carbon capture technologies, these are expected to have the most immediate impact on U.S. pulverized coal power plants.

Utilizing a software infrastructure, CCSI aims to bring new, cost-effective technologies to market in several important ways:

- Promising concepts will be more quickly identified through rapid computational screening of devices and processes.
- Reducing the time and expense to design and troubleshoot new devices and processes through science-based optimal designs.
- More accurately quantifying the technical risk in taking technology from laboratory-scale to commercial-scale.
- Quickly quantifying deployment costs by replacing some of the physical operational tests with virtual power plant simulations.

Under the **Industrial Carbon Capture and Storage (ICCS) Program**, DOE is collaborating with industry in cost-sharing arrangements to demonstrate the next generation of technologies that will capture CO_2 emissions from industrial sources and either store those emissions or beneficially use them. The technologies included in the ICCS Program have progressed beyond the R&D stage to a scale that can be readily replicated and deployed into commercial practice within the industry.

capture, transport, and storage of anthropogenic CO_2. The primary injection well, D9-7#2, was completed December 24, 2011, and the backup well, D9-9#2, which will be used as an observation well, was completed January 22, 2012. Both wells have a total depth of 11,780 feet, but will be plugged back to inject CO_2 into an upper zone, called the Paluxy Formation, between 9,500 and 10,500 feet.

MGSC Large-Scale CO_2 Storage Field Test Begins Injection (2011). The facility that captures, dehydrates, and compresses a portion of the CO_2 stream from the ethanol production fermenters at the Archer Daniels Midland (ADM) Corn Processing Plant in Decatur began to provide CO_2 as a supercritical dense phase fluid to a 6,000-foot pipeline connected to an injection well located on ADM property. With final approval from the Illinois EPA, which issued a final Class I Underground Injection Control (UIC) permit in March 2011, ADM officials plan to inject a total of 1,000,000 metric tons of CO_2 into a target zone approximately 7,000 feet deep in the Mt. Simon sandstone over a three-year period which began in November 2011. The deep, regionally expansive saline reservoir could store billions of tons of CO_2, offering significant opportunities to store the more than 250 million tons of CO_2 produced each year in the Illinois Basin.

Permits Issued for USA's Largest, Fully-integrated CCS Project (2011). The Alabama Department of Environmental Management (ADEM) issued UIC Class V permits for the two injection wells that will be used for injection in a saline-bearing formation, and can later be re-permitted as Class II wells to be used as part of EOR operations by Denbury Resources at the Citronelle Oil Field north of Mobile, Alabama. The permits include supplementary details requested by EPA following a 30-day review of the draft ADEM application. Starting in the third quarter of 2012, up to 550 metric tons-per-day of compressed CO_2 will be pipelined 12 miles to the EOR site from Southern Company's James M. Barry Electric Generating Plant (Plant Barry) in Bucks, Alabama. The CO_2 volume will be captured from a 25 MW-equivalent slip stream of plant flue gas utilizing amine technology licensed by Mitsubishi Heavy Industries America, and injected 9,400 feet into the lower Cretaceous Paluxy Formation. Transportation and injection operations will continue for approximately two years, and subsurface plume movement and storage permanence will be monitored through 2017. This Phase III/large-scale field project will assist in demonstrating the commercial benefits of stacked storage in saline-bearing formations within operating EOR fields.

SECARB's Mississippi Project Hits 1-Million-Ton Milestone for Injected CO_2 (2009). A large-scale CO_2 storage project led by SECARB injected a total of more than 1 million tons of CO_2 at the Cranfield site in Southwestern Mississippi, becoming the fifth project worldwide to achieve that milestone. The Cranfield project combines the use of CO_2 injection with EOR, followed by CO_2 injection into deeper and larger-volume saline formations. Researchers at Cranfield monitored the injected CO_2 with instrumentation installed nearly two miles beneath the surface to ensure the safe and permanent storage in the Lower Tuscaloosa Formations. The Cranfield project also has been successful in the deployment of pressure-response monitoring techniques in the injection zone ("in-zone") and above the injection zone ("above zone"). Real-time data collected since July 2008 has demonstrated that these techniques are cost-effective methods for MVA programs across the United States.

Knowledge Sharing

In order to achieve the commercialization of CO_2 storage technologies, DOE believes that knowledge sharing among various entities is essential. Distribution of the results and lessons learned from both field projects and Core R&D efforts will provide the foundation for future, large-scale CCUS projects across North America and in addressing future challenges associated with public acceptance, infrastructure (pipelines, compressor stations, etc.), and regulatory frameworks. DOE promotes information and knowledge sharing through various avenues including the RCSP working groups, development of best-practices manuals, public outreach and education efforts including the NETL Carbon Storage Program website, assistance providing information to those developing CCUS regulations, and through the ARRA CCUS Training Centers.

Knowledge Sharing Accomplishments

NETL Holds First Annual Carbon Storage Infrastructure Review Meeting (2011). The 2011 Carbon Storage Infrastructure Annual Review Meeting held November 15-17, 2011, in Pittsburgh, Pennsylvania, attracted 186 participants representing the seven RCSPs, state and Federal government agencies, industry, academia, and the interested public. In addition to RCSP progress and key advancements in building critical infrastructure to support commercial geologic storage of CO_2, meeting participants discussed other U. S. and international projects designed to characterize CO_2 storage resource through exploration and injection operations. The 10 Geologic Storage Site Characterization projects supported by the Recovery Act, as well as three recently-awarded small-scale CO_2 injection projects, were among the projects discussed. Two interactive reception/poster sessions featured the work being performed by the seven Recovery Act-supported Regional Carbon Sequestration Training Centers, DOE national laboratories, RCSP subcontractors, and other U.S. and international organizations. The keynote session addressed critical regulatory issues affecting carbon storage, and reviewed a CO_2 pipeline study conducted by the Interstate Oil & Gas Compact Commission (IOGCC). The meeting provided an opportunity to share knowledge of recent achievements and lessons learned by the RCSPs and other carbon storage infrastructure projects for planning future carbon storage efforts.

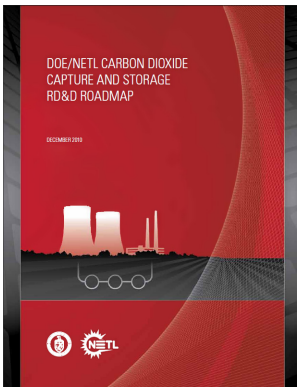
Redesigned NATCARB Viewer Offers Wealth of Information on Worldwide Technology, Projects (2011). An updated and redesigned version of NATCARB was launched on the DOE/NETL website. The interactive online tool integrates a wealth of information about worldwide efforts to deploy CCS technologies. The tabs within NATCARB open different maps for query and analysis capabilities: (1) the RCSP tab shows the seven RCSP regions and provides links to CCS projects undertaken by DOE's RCSP Initiative; (2) the ATLAS tab is the interactive version of data (CO_2 stationary sources, saline formations, oil and gas reservoirs, unmineable coal areas, and sedimentary basins) contained in the 2010 Carbon Sequestration Atlas of the United States and Canada – Third Edition (Atlas III); (3) the FIELD PROJECTS tab shows the locations of CCS field projects and provides links for more information on these small- and large-scale projects, including the 10 Recovery Act site characterization projects; and (4) the WCCS tab shows a user-friendly world map with locations for all active, postponed, canceled, and terminated CCS projects. NATCARB is a GIS-based tool developed to provide a view of CCS potential in the United States and portions of Canada. The updated NATCARB Viewer includes projects and information on the Carbon Storage Program's R&D initiatives to advance geologic CO_2 storage toward commercialization. The information contained in NATCARB is updated quarterly.

NETL Releases Updated Version of the Carbon Storage Program Website (2011). NETL released a new, user-friendly version of the Carbon Storage Program website in early May 2011. The Carbon Storage Program website contains both introductory and in-depth information about storage fundamentals, supporting technologies, storage applications, environmental benefits, and the status of the latest R&D activities. In addition, the website, which is accessible from the NETL homepage, contains updated material on the program's Core R&D, Infrastructure, and Global Collaborations elements; a modified Frequently Asked Questions (FAQ) section; a section highlighting the NATCARB; and an updated Reference Shelf.

Carbon Storage Program Sponsors Research and Development Needs Workshop (2011). The Carbon Storage Program R&D Needs Workshop was held on October 19-20, 2011, in Pittsburgh, Pennsylvania. The workshop focused on the technical aspects of DOE's Carbon Storage Program within the context of an integrated system of capture, transport, and storage set within a corresponding policy and regulatory framework. Approximately 50 members of the CCS community from industry, academia, and government contributed to the success of this workshop. As follow-on to the workshop, a final report was prepared, summarizing both the research gaps and needs discussed and prioritized at the workshop. The research needs were categorized as short-term (less than five years), mid-term (5 to 10 years), and long-term (greater than 10 years).

SECARB
Southeast Regional Carbon Sequestration Partnership

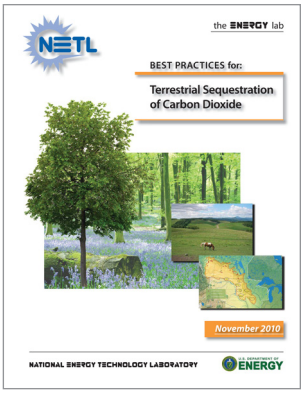
State Regulatory Framework Will Most Likely Result in Robust CO_2 Pipeline System, New Study Says (2011). According to an NETL-funded report, the approach most likely to result in a strong CO_2 pipeline system in the United States will be a private sector model with a state-based regulatory framework. However, the study also notes that a Federal role, which would encourage private construction of CO_2 pipelines through incentives, would also be important in the future. The report, titled, "A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide," analyzes a potential pipeline network that would transport CO_2 from large CO_2 stationary sources to underground storage locations. A pipeline network is believed to be an important component to commercialize and deploy CCS technology to reduce the buildup of CO_2 in the atmosphere. The report, which was undertaken by the DOE-funded Pipeline Transportation Task Force (PTTF), was developed by SECARB and IOGCC. The data collected for the report is expected to improve commercialization efforts by analyzing current CO_2 storage situations and identifying what is needed for viable transport to storage areas.



New Roadmap Updates Status of DOE CCS RD&D Efforts (2011). DOE published a roadmap that provides an overview of research, development, and demonstration (RD&D) efforts to supply cost-effective, advanced CCS technologies for coal-based power systems. The "DOE/NETL Carbon Dioxide Capture and Storage RD&D Roadmap" outlines the efforts to develop advanced CCS technology, as well as several technologies being pursued to mitigate risks inherent to RD&D efforts. DOE anticipates that an array of advanced CCS technologies will be ready for large-scale demonstration by 2030, providing safe, cost-effective carbon management to meet national goals for reducing GHG emissions. Research success will enable CCS technologies to overcome a wide range of challenges, such as successful integration of CO_2 capture, compression, transport, and storage technologies with power generation systems; effective CO_2 MVA; permanence of underground CO_2 storage; and public acceptance.

DOE BPM Focuses on Site Selection for CO_2 Storage (2011). DOE released a BPM focusing on the most promising methods for assessing potential CO_2 geologic storage sites. Developed by NETL, the manual, titled, "Site Screening, Site Selection, and Initial Characterization for Storage of CO_2 in Deep Geologic Formations," will continue to be used as a resource by future project developers and CO_2 producers and transporters. In addition, the BPM will be used to inform government agencies of the best practices for exploring potential CO_2 geologic storage sites and to educate the public. This is the fourth BPM released by DOE, and it provides a framework for reporting resources calculated using methods developed by DOE, CSLF, and others. This BPM focuses on the exploration phase of the site characterization process and communicates analyses and guidelines for narrowing potential sub-regions into qualified sites for CO_2 geologic storage. Development of the geologic storage system proposed in this BPM has been instrumental in establishing consistent, industry-standard terminology and guidelines for communicating storage resources and storage resource estimates, as well as project risks, to stakeholders.

DOE Manual Studies Terrestrial Carbon Sequestration (2011). According to a Best Practice Manual (BPM) released by DOE, titled, "Best Practices for Terrestrial Sequestration of Carbon Dioxide," there is considerable opportunity and growing technical sophistication to make terrestrial carbon storage both practical and effective. The BPM details the most suitable operational approaches and techniques for terrestrial CO_2 storage, which uses photosynthesis to create organic matter that is stored in vegetation and soils; this is different from CO_2 mitigation technologies that focus on capturing and permanently storing anthropogenic CO_2 emissions. NETL used data from the seven RCSPs to prepare the BPM, which also discusses the analytical techniques necessary to monitor, verify, and account for terrestrially stored carbon. In addition, results from the RCSPs' terrestrial field projects are presented. The best practices outlined in this BPM will help those interested in pursuing terrestrial storage projects, as well as those interested in regulating them, to optimize their efforts.



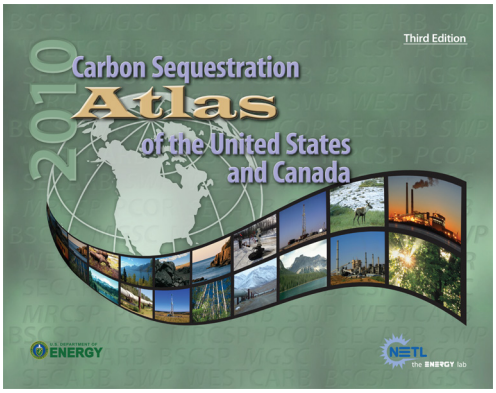
DOE Best Practices Manual Focuses on Site-Specific Management Activities for Carbon Storage Well Systems (2011). DOE completed and published a BPM, titled "Carbon Storage Systems and Well Management Activities," which is intended to share lessons learned regarding management activities for carbon storage well systems. The purpose of this BPM is to provide an overview of the management activities typically associated with CCS projects for those involved in the development and implementation of CCS projects, governmental agencies, and other non-governmental organizations. Specifically, this manual focuses on management activities related to the planning, permitting, design, drilling, implementation, and decommissioning of wells for geologic storage. A key lesson/theme reiterated in this manual, and the other BPMs, is that each project site is unique, meaning that each CCS project needs to be designed to address specific site characteristics and should involve an integrated team of experts from multiple technical and non-technical disciplines. Additionally, results developed during the characterization, siting, and implementation phases of projects are iterative; the results from previously completed tasks are analyzed and used to make decisions going forward. This means that as data becomes available, the site conceptual model is revised and updated to allow for better future decisions.

DOE Best Practices Manual Illustrates the Concepts of Risk Analysis and Numerical Simulation (2011). DOE released a BPM, titled "Risk Analysis and Simulation for Geologic Storage," that builds upon the experience of the RCSP initiative and efforts within the research community to develop an approach for utilizing risk analysis and numerical simulation for a CO_2 storage project. Risk analysis and numerical simulation are critical tools used iteratively in conjunction with site characterization, monitoring, and public outreach throughout all of the stages of a geologic CO_2 storage project to help meet the goals of safe, secure, and verifiable permanent storage. Risk analysis and numerical simulations will guide CCS implementation by providing stakeholders (operators, project developers, general public, and regulators) with information to predict the long-term fate of CO_2. The BPM illustrates the concepts of risk analysis (risk assessment) and numerical simulation by describing the experience gained by the RCSPs as they implemented multiple field projects.

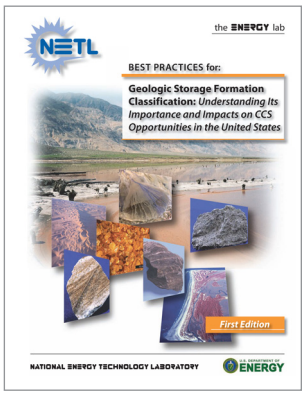
STEP Hosts 2011 IEA GHG International CCS Summer School (2011). The Sequestration Training and Education Program (STEP), led by the Illinois State Geologic Survey in cooperation with MGSC, held the 2011 IEA GHG Summer School event at the University of Illinois Champaign Campus. A total of 53 Ph.D. and post-doc students from around the world with backgrounds in engineering, geo-technologies, and socio-economics received five days of class work, as well as a site visit to the MGSC large-scale CO_2 injection demonstration project in Decatur to see an operational CCS facility. Student attendees, who earned a cumulative total of 265 Continuing Education Units (CEU), learned about all aspects of the MGSC Development Phase project (DE-FC26-05NT42588) to inject and store 1 million metric tons of CO_2 in the Mt. Simon Sandstone. The site visit included insight into capture; compression and dehydration; MVA; well construction; data gathering and management; and project development, site best practices, and project management. The IEA GHG, based in the United Kingdom, studies and evaluates technologies that can reduce GHG emissions derived from the use of fossil fuels. The Summer School program is

designed to provide students with definitive information on the role that technology can play in reducing GHG emissions and encourage their active participation in future developments.

DOE Collaborates with BOEM to Document Regulations for Offshore CCS Operations (2011). On January 20-21, 2011, the IOGCC, in conjunction with the Southern States Energy Board (SSEB), held meetings in New Orleans to kick off the IOGCC/SSEB Offshore and Regulatory Task Force. The primary objective of the Task Force is to evaluate the potential for geological storage of CO_2 utilizing existing offshore oil and natural gas fields in the Gulf of Mexico nearing the end of productive life, as well as in areas that have not been subject to oil and natural gas production, such as along the eastern seaboard of the United States. The offshore geologic settings may be suitable for CO_2 storage with the adaptation of technical, regulatory, and business modifications. The Task Force will perform resource mapping of CO_2 storage potential and infrastructure in offshore areas under Federal jurisdiction, as well as offshore areas under state jurisdiction. The current legal and regulatory structures will also be evaluated. Technical and legal representatives from several coastal states attended, as well as representatives from IOGCC, SSEB, NETL (DOE), and BOEM (DOI).



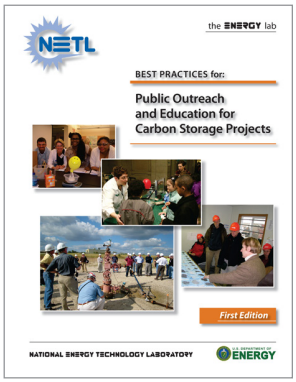
Third Carbon Sequestration Atlas Estimates Up to 5,700 Years of CO_2 Storage Potential in U.S. and Portions of Canada (2010). On December 1, 2010, DOE released the "Carbon Sequestration Atlas of the United States and Canada – Third Edition (Atlas III)," which documents 1,800 billion to more than 20,000 billion metric tons of CO_2 storage resource potential in saline formations, oil and gas reservoirs, and unmineable coal areas in the United States and portions of Canada. This suggests a potential 500 to 5,700 years of potential CO_2 storage resource in assessed geologic formations. In addition, Atlas III provides updates on RCSPs activities, DOE's Carbon Storage Program, international CCS collaborations, worldwide CCS projects, CCS regulatory issues, and CO_2 stationary source emissions. The CO_2 storage resource calculation methodology of *Atlas III* was refined to better reflect uncertainties in geologic formation properties. Two versions of Atlas III are available: (1) an interactive version located on the NATCARB website, and (2) a print version available for download on the NETL website.



DOE Manual Studies 11 Major CO_2 Geologic Storage Formations (2010). DOE issued a manual containing a comprehensive study of 11types of geologic formations suitable for permanent underground CO_2 storage. The NETL-developed manual used data from DOE's RCSPs and other research activities to describe the characteristics of geologic formations that could potentially be used for carbon storage. One of DOE's program goals is to identify geologic formations that can store large volumes of CO_2, receive CO_2 at an efficient and economic rate of injection, and safely retain it over long periods of time. These three criteria are investigated in the manual for 11 major geologic reservoirs. In addition, the manual builds on lessons learned from CO_2 behavior in geologic reservoirs during earlier investigations. The information provided by the manual is expected to allow government agencies and their project partners and/or private investors to optimize their storage efforts.)

Interagency CCS Task Force Provides Recommendations on Fostering Clean Coal Technology (2010). The Interagency Task Force on CCS delivered a series of recommendations on August 12, 2010, for achieving the widespread, cost-effective deployment of CCS within 10 years. The report concludes that CCS technologies can be vital in reducing domestic GHG emissions while preserving the option of using coal and other domestic fossil energy resources. The main findings of the report include: CCS is viable, a carbon price is critical, Federal coordination should be strengthened, and long-term liability could be a barrier to CCS deployment. The report contains input from 14 Federal agencies and departments,

stakeholders, and CCS experts. In addition, the report addresses incentives for CCS adoption and a number of financial, economic, technological, legal, and institutional barriers to deployment; how best to coordinate existing Federal authorities and programs; and areas where additional Federal authority may be necessary.



DOE Publishes BPM for Public Outreach and Education for Carbon Storage Projects (2010). DOE released a BPM, titled, "Best Practices for Public Outreach and Education for Carbon Storage Projects," intended to assist project developers in understanding and applying best outreach practices for siting and operating CO_2 storage projects. The manual provides practical, experience-based guidance on designing and conducting effective public outreach activities. The primary lesson learned from the RCSPs' experience is that public outreach should be an integrated component of project management. It also concludes that conducting effective public outreach will not necessarily ensure project success, but underestimating its importance can potentially contribute to project delays, increased costs, and lack of community acceptance. In addition to the finding that public outreach should be an integral component of project management, the manual outlines an additional nine best practices. In combination, these 10 practices represent a framework for designing an outreach program that is tailored to the specific characteristics of a planned project, the project developers, and the community in which the project is planned. The recommendations are based on lessons learned by DOE's seven RCSPs during the first six years of the program.

Recovery Act-Funded Regional Sequestration Technology Training Projects Initiated (2009). Seven projects designed to facilitate the transfer of knowledge and technologies for site development, operations, and monitoring of commercial CCS efforts were kicked-off as part of the Annual RCSP Review Meeting held in November, 2009. A special session on Regional Sequestration Technology Training was arranged at the meeting to encourage regional collaborations and to leverage work already completed by the Partnerships. The NETL-managed, three-year training grants are valued at approximately $8.47 million—including cost share from the private sector—and will produce the workforce necessary for the CCS industry with skills and competencies in geology, geophysics, geomechanics, geochemistry, and reservoir engineering disciplines.

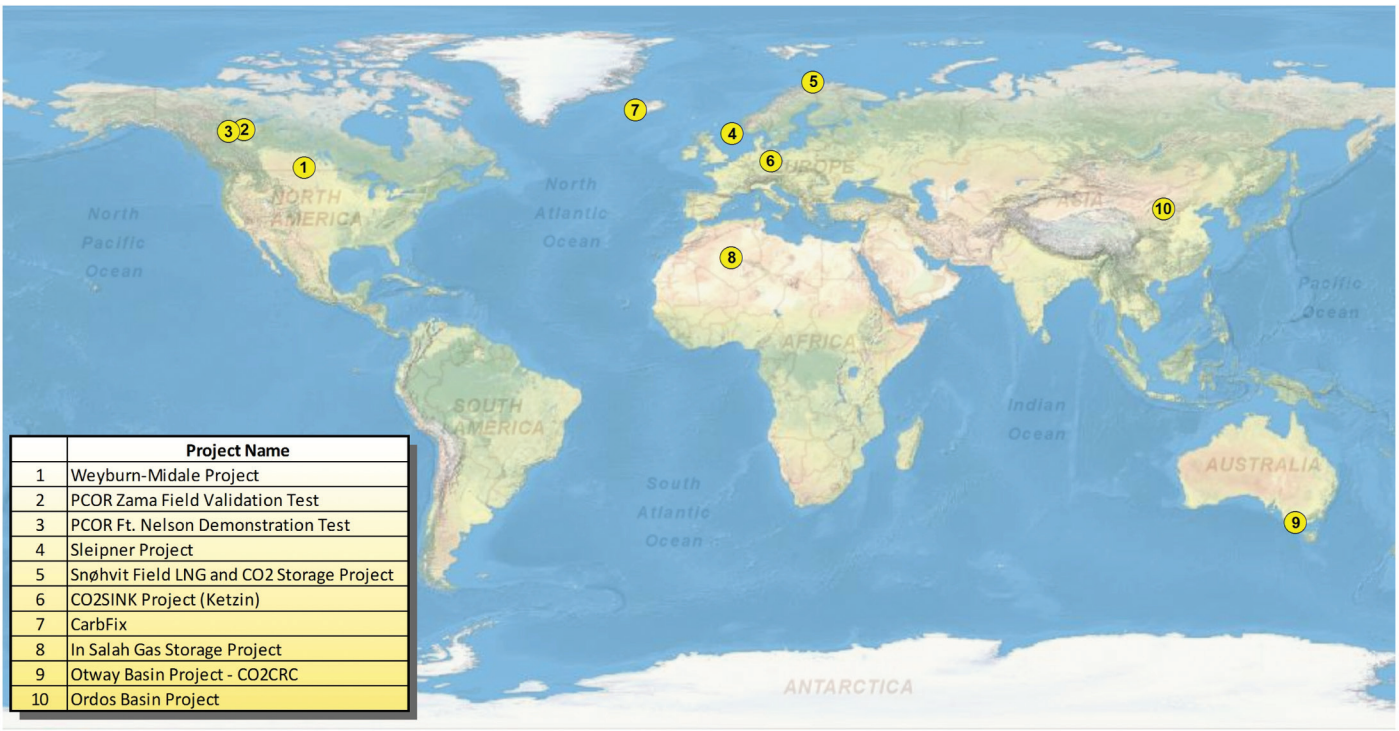
Global Collaborations Accomplishments

The Global Collaborations Element includes ongoing partnerships 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, CERC, and NACAP.

International Demonstration Projects

DOE enters into partnerships with many international organizations to advance research in carbon storage. The efforts under the Global Collaboration Element benefit from technology solutions developed through the Carbon Storage Program's Core R&D and Infrastructure Elements. These collaborative learning opportunities will help to advance CCUS technologies at a lower cost and on a shorter timeframe. The benefits of U.S. scientists' participation range from opportunities to field test innovative technologies at commercial and large-scale CCUS operations around the world to representing U.S. expertise on multinational CCUS investigative R&D teams. Supporting these projects directly enhances U.S. efforts to develop technologies and tools to meet the strategic goals of the Carbon Storage Program's Core R&D Element. The figure below displays the location of each DOE-supported international CCUS demonstration project.

In addition, these collaborations provide a means to encourage the transfer of technical lessons learned between industry and academia to facilitate the adoption of these technologies in the field. It will train personnel in the United States and abroad for future careers in the CCUS industry. The table below details DOE-supported international CCUS projects.



	Project Name
1	Weyburn-Midale Project
2	PCOR Zama Field Validation Test
3	PCOR Ft. Nelson Demonstration Test
4	Sleipner Project
5	Snøhvit Field LNG and CO2 Storage Project
6	CO2SINK Project (Ketzin)
7	CarbFix
8	In Salah Gas Storage Project
9	Otway Basin Project - CO2CRC
10	Ordos Basin Project

Figure 11: Location of DOE-Supported International CCUS Demonstration Projects

Table 1: DOE-Supported International Demonstration Projects

Project Location Project Name	Operations	Reservoir Storage Type	Operator/Partner	DOE Contribution
North America, Canada Saskatchewan Weyburn-Midale	2.8 MMt CO_2/yr	oil field carbonate EOR	Cenovus, Apache, Petroleum Technology Research Center	DOE is supporting scientists to test multiple monitoring and simulation technologies.
North America, Canada Alberta Zama Oil Field	25,000 Mt CO_2/yr	oil field carbonate EOR	Apache, PCOR Partnership (RCSP)	Supporting the PCOR Partnership to conduct monitoring and reservoir modeling of CO2 injection into pinnacle reefs.
North America, Canada British Columbia Fort Nelson	> 1 MMt CO_2/yr	saline carbonate formation	Spectra Energy, PCOR Partnership (RCSP))	Supporting PCOR Partnership to conduct monitoring and reservoir modeling studies.
Europe, North Sea, Norway Sleipner	1 MMt CO_2/yr	saline marine sandstone	StatoilHydro	Supported the Scripps Institute of Oceanography to conduct repeat gravity surveys.
Europe, North Sea, Norway Snøhvit CO_2 Storage	700,000 metric tons CO_2/yr	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 metric tons CO_2	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 metric tons CO_2	gas field and saline sandstone	CO_2CRC	Supporting scientists at LBNL to test multiple monitoring technologies at depleted gas fields and saline formations.
Africa, Algeria In Salah Gas	1 MMt CO_2/yr	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 metric tons CO_2/yr	Ordos Basin	Shenhua Coal	Supporting West Virginia University and LLNL to assess resource for storage, and simulating hydrogeologic and geochemical reservoir conditions.

International Demonstration Projects Accomplishments

Icelandic CarbFix Pilot Successfully Begins CO_2 Basalt Storage (2011). Working in cooperation with NETL, Columbia University researchers are testing the effectiveness of radiocarbon and another tracer, trifluormethylsulphur pentafluoride, for tracking the movement and geochemical reactions associated with CO_2 injected into basalt formations. The experiment is part of Iceland's CarbFix Pilot Project, which initiated CO_2 injection into the basalt reservoir at the Hellisheidi geothermal power plant. Operated by Reykjavik Energy, the plant can produce up to 213 MW of power and 60,000 tons of CO_2 per year from geothermal gases rising in wells drilled 2,000 meters deep. Carbon dioxide separated from the geothermal gases is dissolved in water at elevated pressure and injected into the basalt reservoir at an approximate depth of 600 meters just outside the boundary of the geothermal system. More than 90 percent of Iceland is made of basalt, which contains reactive minerals and glasses with high potential for CO_2 storage. The project team aims to accelerate the natural reaction of the carbonated liquid with calcium in the basalt to form calcite, which is stable for thousands of years in geothermal systems. Other project partners represent the University of Iceland and the National Center for Scientific Research in Toulouse, France.

U.S. Partners with Canada to Renew Funding for World's Largest International CO_2 Storage Project in Depleted Oil Fields (2010). DOE and Natural Resources Canada (NRCan) announced they would commit $5.2 million to bring the International Energy Agency (IEA) Greenhouse Gas Weyburn-Midale CO_2 Monitoring and Storage Project to conclusion in 2011. The funding, of which DOE is providing $3 million and the Government of Canada is providing $2.2 million, will allow the final phase of the project to focus on best practices for the safe and permanent storage of CO_2 with EOR; support research to solidify the knowledge of MVA in depleted oil reservoirs; and demonstrate the safe storage of CO_2. Weyburn-Midale is conducted in conjunction with $2 billion of commercial CO_2 injection operations, which to date have stored 18 million tonnes of CO_2 into the Weyburn and Midale oil fields located in Saskatchewan, Canada. Approximately 40 million tonnes of CO_2 are expected to be stored over the life of the EOR operations.

European Commission Selects Two Projects Involving DOE-Supported U.S. Teams (2010). One of the projects selected for partial funding under the European Commission's (EC) 7th Framework Programme will be coordinated by the Natural Environment Research Council with participation by researchers at Montana State University and Stanford University in fundamental research on the potential environmental impacts of CO_2 storage. U.S. partners LBNL, PNNL, and the Gulf Coast Carbon Center of the Texas Bureau of Economic Geology will make scientists and numerical platforms for modeling studies available to the project.

Australian Otway Basin CO_2 Storage Project Enters New Phase (2010). As part of an NETL-supported Field Work Proposal (FWP), investigators at LBNL provided assistance in the design of a second injection well drilled for the Otway Project in Victoria led by the Cooperative Research Centre for Greenhouse Gas Technologies (CO_2CRC). Once the new well was drilled to a depth of 1,500 meters, CO_2 injected at a depth of 1,400 meters will be used to evaluate several types of CO_2 trapping mechanisms and refine methods of monitoring geologic storage of CO_2. DOE supported the initial injection test through LBNL's design, fabrication, and installation of the Naylor-1 monitoring well bottom hole assembly and instrumentation. Australia's first CO_2 storage project, the CO_2CRC Otway Project has successfully injected, stored, and monitored more than 60,000 tonnes of CO_2 since April 2008 in a depleted gas reservoir more than a mile beneath the earth's surface.

Figure 12: CSLF Logo

Carbon Sequestration Leadership Forum

CSLF is a voluntary climate initiative of industrially developed and developing nations that account for about 77 percent of all manmade CO_2 emissions. CSLF gathers intellectual, technical, and financial resources from all parts of the world to support the long-term goal of the United Nations Framework Convention on Climate Change (UNFCCC) – the stabilization of atmospheric CO_2 concentrations in this century. Joint efforts by DOE and the U.S. Department of State established CSLF in 2003 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 CCUS on a global scale.

Carbon Sequestration Leadership Forum Accomplishments

Energy Ministers Endorse CCUS as Key to Combating Climate Change (2011). In an official announcement made by member country ministers and heads of delegation, CSLF endorsed carbon capture, utilization, and storage (CCUS) technologies as a significant component of international plans to combat climate change. The CSLF member nations affirmed CCUS as an important element of any effective response to climate change and suggested an increase in the number of worldwide demonstrations in order to enable commercial deployment of CCUS by the end of the decade.

World-Class CCS Projects Honored by International Body (2011). CSLF selected three projects pioneering CCS technologies at a large commercial scale to receive its Global Achievement Award. Each of the three projects reached milestones with sustained operation demonstrating capture, injection, and storage of several million tonnes of CO_2. The three recipients of the award are: the In Salah CO_2 Storage Project in Algeria; the Sleipner CO_2 Project in the North Sea; and the Weyburn-Midale CO_2 Project in Canada. In addition to providing scientific research opportunities, the projects are also being recognized as exemplary global models for their willingness to share their experiences in implementing CCS technologies.

Advancement of CCS Contingent on Addressing Key Issues (2010). CSLF released a report, titled, "CSLF's 2010 Technology Roadmap," that states significant international progress on advancing CCS has been made in the past year, and that a number of important challenges must be addressed in order for widespread commercial deployment to be achieved. In addition, the report notes that globally significant national investments are occurring to advance the deployment of CCS technologies. There are 32 active or completed CSLF-recognized projects that demonstrate worldwide collaboration on CCS and contribute to the CCS knowledge base.

CSLF Recognizes SECARB (2010). Dr. Susan Hovorka accepted an award on behalf of SECARB at the CSLF Policy and Technical Groups meeting on October 6-8, 2010, in Warsaw, Poland. Dr. Hovorka, of the Texas Bureau of Economic Geology, is a lead researcher for the SECARB Cranfield project designed to determine whether the immediate commercial benefit of EOR can offset infrastructure development costs for follow-on, large volume, long-term storage of CO_2 in underlying saline formations.

Worldwide CCUS Projects Database

NETL's CCUS Projects Database includes active, proposed, canceled, and terminated CCUS projects worldwide. Information in the database regarding technologies being developed for capture, evaluation of sites for CO_2 storage, estimation of project costs, and anticipated dates of completion is sourced from publically available information. The CCUS Database provides the public with information regarding efforts by various industries, public groups, and governments towards development and eventual deployment of CCUS technology.

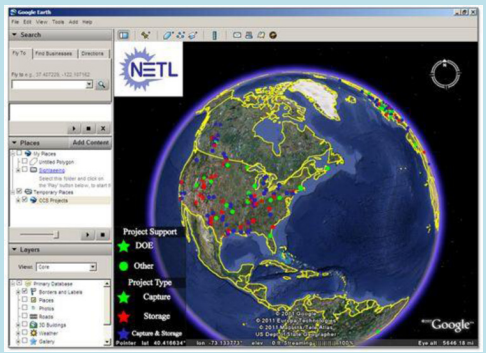


Figure 13: NETL's CCUS Projects Database

North American Carbon Atlas Partnership

NACAP is a mapping initiative designed to disseminate and exchange CCS-related information among the United States, Canada, and Mexico to effectively speed the development of a CO_2 sources and GIS database in North America. The development of this GIS system supports DOE's Carbon Storage Program in DOE's Office of Fossil Energy, the objectives of NAEWG, and current initiatives under the Canada-United States Clean Energy Dialogue and the Mexico-United States Bilateral Framework on Clean Energy and Climate Change. It is expected that this initiative will demonstrate collaboration among the three countries in the area of CCS.

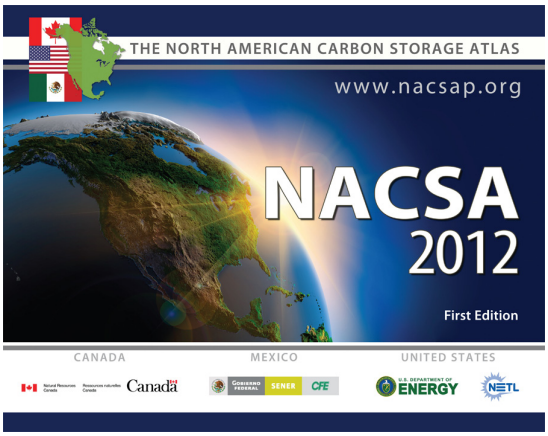
Figure 14: NACAP Logo

Worldwide CCUS Projects Database Accomplishments

Worldwide CCS Projects on the Increase (2009). According to a DOE online database, worldwide efforts to fund and establish CCUS projects have accelerated. A project of DOE and NETL, the CCUS Database reveals proposed and active CCUS projects worldwide. The database also provides information about the efforts of various industries, public groups, and governments to develop and deploy CCUS technology; lists technologies being developed for capture, testing sites for CO_2 storage, and estimations of costs and anticipated project completion dates; and uses Google Earth to illustrate the location of projects and provide links for further information in a user friendly application. The database will be updated as more information becomes available.

North American Carbon Atlas Partnership Accomplishments

DOE Announces New Mapping Initiative to Advance North American Carbon Storage Efforts (2012). DOE, with partners from Canada and Mexico, released the North American Carbon Storage Atlas (NACSA), the first-ever atlas mapping the potential CO_2 storage resource in North America. According to NACSA, North America contains at least 500 years of geologic storage resource for CO_2 emissions that result from either industrial sources or power plants. In addition to estimating storage resource for North American oil and gas fields, unmineable coal, and saline formations, NACSA also documents the location of approximately 2,250 large stationary CO_2 sources, which, along with documenting the locations of storage potential of various geological sites, helps



quantify the benefits and opportunities for potential CCS projects. Created through NACAP and developed by DOE, Natural Resources Canada, and the Mexican Ministry of Energy, NACSA also includes work from DOE's RCSPs, whose 400 organizations provide input to DOE/NETL's National Carbon Sequestration Database and Geographic Information System. A hardcopy version, website, and interactive viewer are available online.

5th Meeting of the North American Carbon Atlas Partnership (2011). The fifth meeting of the North American Carbon Atlas Partnership (NACAP 5) took place in Morgantown, West Virginia, on April 5 and 6, 2011. The United States was the host country, and the meeting venue was split between West Virginia University and DOE/NETL. The 29 participants included 4 from Canada, 3 from Mexico, 1 from the United Kingdom, and 21 from the United States.

U.S.-China Clean Energy Research Center

Figure 15: CERC Logo

CERC is a collaboration between the United States and China to facilitate joint research and development to accelerate clean energy technologies. Established in 2009, the $150 million center further extends the decades of previous science and technology collaboration between the United States and China. The center's funding is split equally between the two countries, and involves participation from academia, research laboratories, and industry. U.S. funds are being used to support work conducted by U.S. institutions and individuals and Chinese funds are supporting work conducted by Chinese institutions and researchers.

U.S.-China Clean Energy Research Center Accomplishments

NETL Signs Technical Cooperation Agreement with Chinese Clean Energy Company (2010). NETL officials and representatives from the ENN Group signed a five-year Project Agreement for R&D cooperation developed under Annex IV (Energy & Environmental Control Technologies) of the U.S.-China Fossil Energy Cooperation Protocol. ENN Group is a large vertically integrated Chinese energy supplier that is developing zero-emission coal-based power, carbon capture, and renewable energy technologies. Consistent with diplomatic and commercial initiatives focused on energy and the environment, including the U.S.-China Clean Energy Research Center, the agreement aims to advance development of clean coal technologies of interest to both countries through collaborative R&D, modeling and simulation, researcher exchanges, joint publications, and other appropriate activities.

Wyoming and Shanxi Sign MOU on Geologic CO_2 Storage Cooperation (2009). The Wyoming State Geological Survey and Shanxi (China) Provincial Science and Technology Commission signed a Memorandum of Understanding (MOU) affirming mutual interest in advancing the science and technology of geologic CO_2 storage through cooperation. Consistent with the priorities of the U.S.-China Clean Energy Research Center (CERC), data sharing, cooperative problem solving, fieldwork, and site visits will contribute to developing the knowledge base and expertise needed for future deployment of these technologies in Wyoming State and Shanxi Province, which produce the most coal in their respective countries. The partnership has been supported by NETL through the Cleaner Fossil Energy Task Force of the Asia Pacific Partnership on Clean Development and Climate.

Contact Information

The NETL website (http://www.netl.doe.gov) offers extensive information about the components of DOE's Carbon Storage Program. The website provides an extensive program overview webpage with details about the technical Core R&D focus areas, Systems Analyses capabilities, an 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 Storage Reference Shelf on the NETL website. Each of the categories on the Carbon Storage 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 Storage Program, please contact John Litynski at John.Litynski@netl.doe.gov, Traci Rodosta at Traci.Rodosta@netl.doe.gov, or Beth Cameon at Beth.Cameon@netl.doe.gov.

Carbon Storage Program
2010–2011 Accomplishments

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