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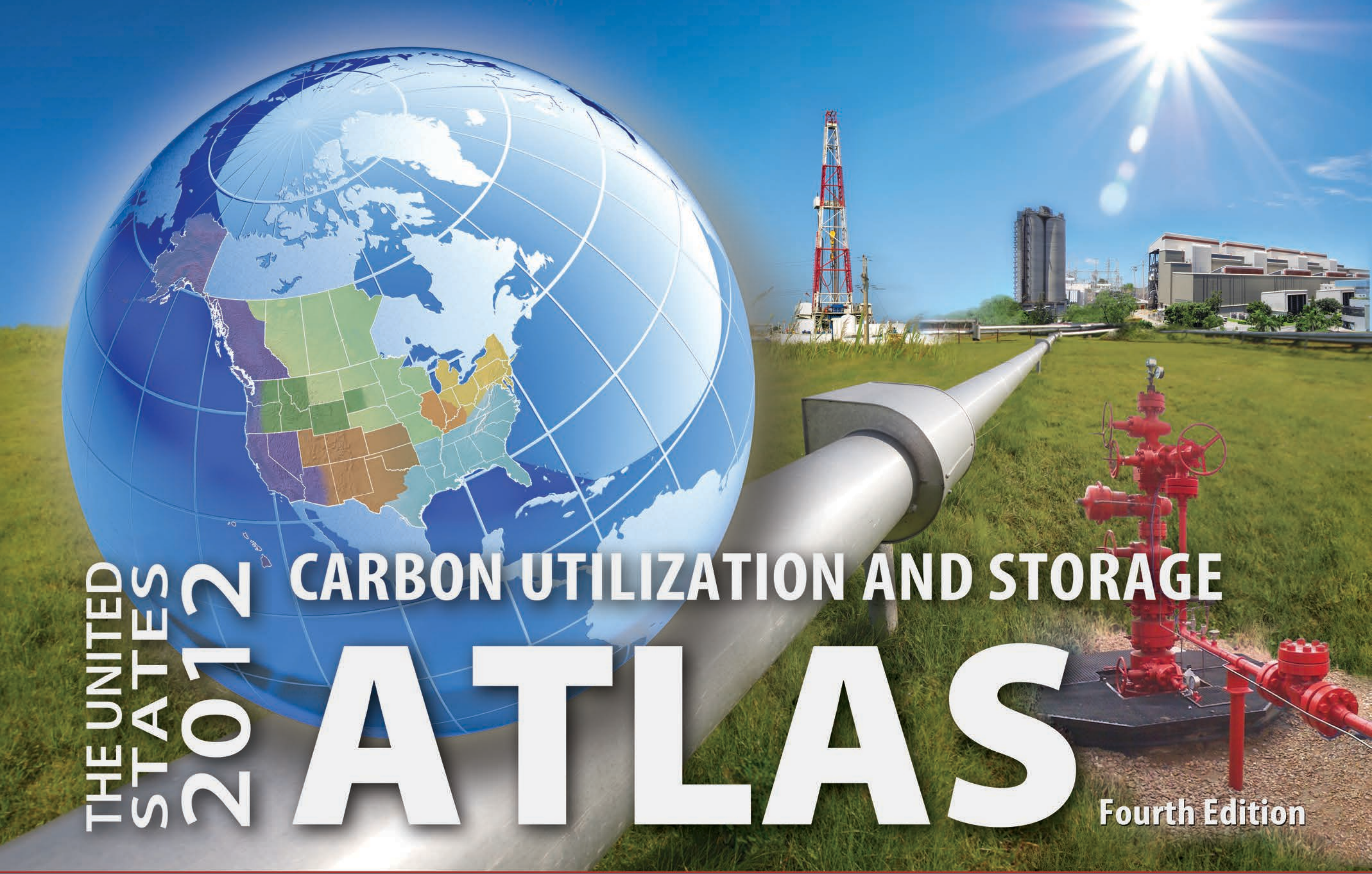

THE UNITED STATES 2012 CARBON UTILIZATION AND STORAGE ATLAS

Fourth Edition

U.S. DEPARTMENT OF ENERGY | Office of Fossil Energy | NETL

Foreword

The U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) is proud to release the fourth edition of the *United States Carbon Utilization and Storage Atlas (Atlas IV)*. Production of *Atlas IV* is the result of collaboration among carbon storage experts from local, State, and Federal agencies, as well as industry and academia. *Atlas IV* provides a coordinated update of carbon capture, utilization, and storage (CCUS) potential across the United States and other portions of North America. The primary purpose of *Atlas IV* is to update the carbon dioxide (CO_2) storage potential for the United States and to provide updated information on the Regional Carbon Sequestration Partnerships' (RCSPs) field activities and new information on the American Recovery and Reinvestment Act of 2009 (ARRA) funded Site Characterization projects. In addition, *Atlas IV* outlines DOE's Carbon Storage Program, DOE's CCUS collaborations, worldwide CCUS projects, and CCUS regulatory issues; presents updated information on the location of CO_2 stationary source emissions and the locations and storage potential of various geologic storage sites; and further provides information about the commercialization opportunities for CCUS technologies from RCSPs.

A key aspect of CCUS deals with the amount of carbon storage potential available to effectively help reduce greenhouse gas emissions. As demonstrated in *Atlas IV*, CCUS holds great promise as part of a portfolio of technologies that enables the United States and the rest of the world to effectively address climate change while meeting the energy demands of an ever increasing global population. *Atlas IV* includes the most current and best available estimates of potential CO_2 storage resource determined by a methodology applied consistently across all of the RCSPs. A CO_2 storage **resource** estimate is defined as the fraction of pore volume of porous and permeable sedimentary rocks available for CO_2 storage and accessible to injected CO_2 via drilled and completed wellbores. Carbon dioxide storage resource assessments do not include economic, or regulatory constraints; only physical constraints are applied to define the accessible part of the subsurface. Economic and regulatory constraints are included in geologic CO_2 **capacity** estimates.

The data in *Atlas IV* is current as of November 2012. It will be updated every two years as new data are acquired and methodologies for CO_2 storage estimates improve. Furthermore, it is expected that, through the ongoing work of the RCSPs, data quality and conceptual understanding of the CCUS process will improve, resulting in more refined CO_2 storage resource estimates.

About *Atlas IV*:

The *United States Carbon Utilization and Storage Atlas* contains four main sections: (1) Introduction; (2) National Perspectives; (3) Regional Perspectives (RCSPs); and (4) ARRA Site Characterization Projects. The Introduction section contains an overview of CCUS technologies, a summary of DOE's Carbon Storage Program, a brief description of the RCSP Program, and information on the National Carbon Sequestration Database and Geographic Information System (NATCARB). The National Perspectives section contains maps showing the number, location, and magnitude of CO_2 stationary sources in the United States, as well as the areal extent and estimated CO_2 storage resource available in geologic formations evaluated within the RCSP regions. The Regional Perspectives section includes a detailed presentation of CO_2 stationary sources, CO_2 storage resource assessments, updates on field projects, and additional information key to each RCSP. Finally, the ARRA Site Characterization Projects section includes a detailed background of each project, its objectives, and a status update.

Carbon dioxide storage resource estimates were derived from data collected by each RCSP and ARRA Site Characterization project. This data is representative of each RCSP region and required estimation of parameters, such as area (A), thickness (h), and porosity (ϕ) for each candidate storage formation. The data were compiled in NATCARB. National CO_2 emission maps and CO_2 storage resource maps were developed for *Atlas IV* from the information provided by the RCSPs and ARRA Site Characterization projects. Carbon dioxide emission maps show the location and magnitude of CO_2 stationary sources. The national CO_2 storage resource maps illustrate areas of potential CO_2 storage.

Carbon dioxide geologic storage information in *Atlas IV* was developed to provide a high-level overview of CO_2 geologic storage potential across the United States. Areal extents of geologic formations and CO_2 resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation of the extent to which geologic CO_2 storage is feasible. This information is not intended as a substitute for site-specific characterization, assessment, and testing.

DOE thanks the many individuals who contributed to *Atlas IV*.

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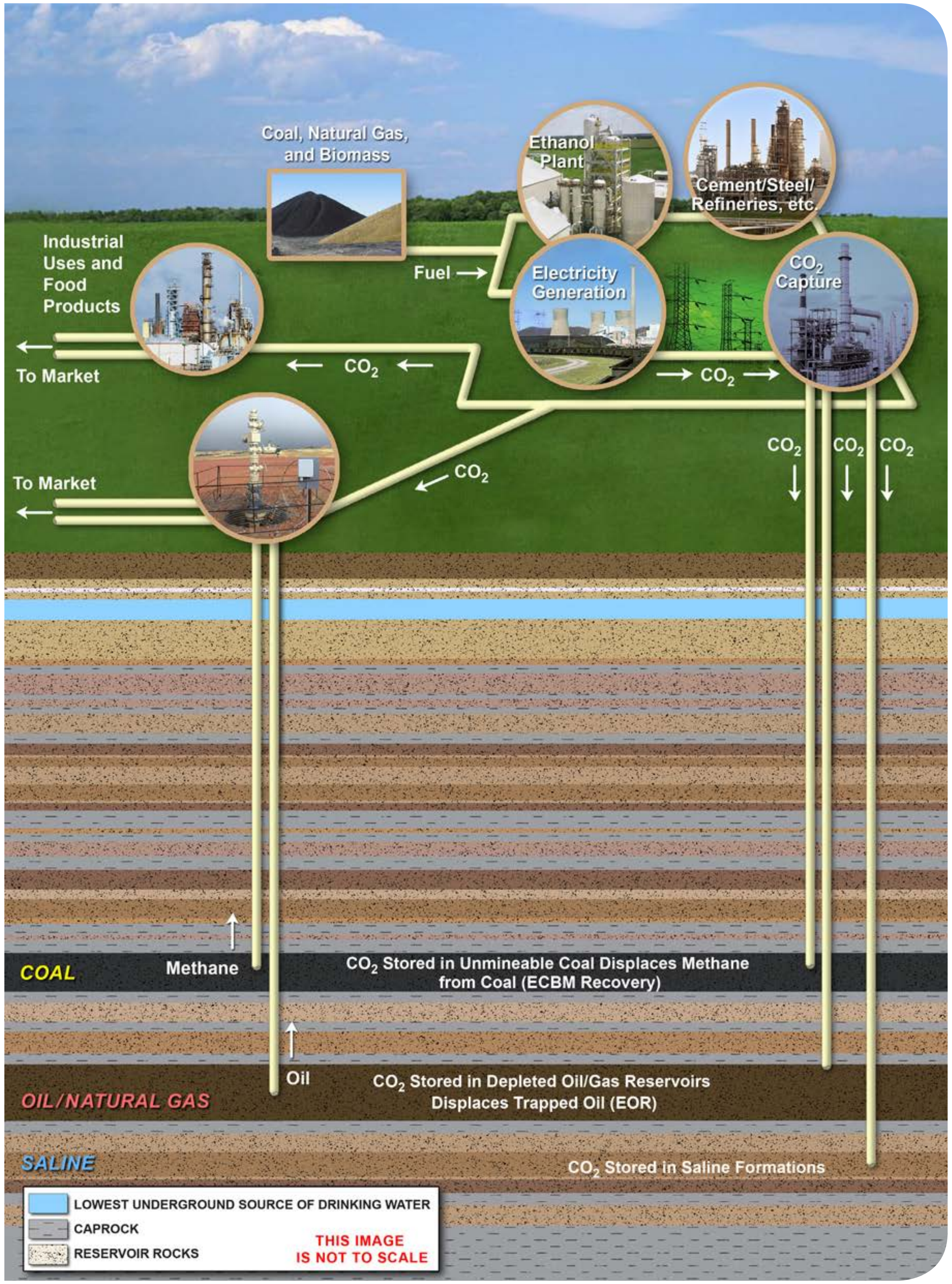


What is Carbon Capture, Utilization, and Storage?

Carbon capture, utilization, and storage (CCUS) consists of a suite of technologies that can benefit an array of industries, including power plants (fossil, biofuel, and geothermal), refineries, and other industrial sources. Its future role in an "all of the above" energy strategy will require that industry considers carbon management as a key issue that must be addressed. A balance is needed between energy security and growing concerns over the impacts of increasing concentrations of greenhouse gases in the atmosphere—particularly CO_2 emissions. At present, approximately one-third of the CO_2 emissions in the United States come from power plants and other industrial facilities contribute approximately one-third of the remaining emissions. The opportunity to apply CCUS to these facilities will have significant benefits for the U.S. economy and environment.

CCUS involves the separation and capture of CO_2 prior to atmospheric release from industrial sources followed by transport and safe, permanent injection into deep underground geologic formations. CCUS enables industry to continue to operate while emitting fewer greenhouse gas emissions, making it a powerful tool to address climate change. Many studies show that CCUS could make a significant contribution to reducing CO_2 emissions.

Carbon dioxide is a commodity used to build business cases for enhanced oil and gas recovery. The United States is fortunate to have a long history of oil production over the past 100 years, as well as more than 40 years of EOR utilizing CO_2. In 2010, approximately 50 million metric tons (MMt) of CO_2 per year from naturally occurring sources were used to recover additional oil. There is an opportunity to supplement and eventually replace the naturally occurring CO_2 used for EOR with CO_2 from anthropogenic sources, reducing the carbon footprint of these fuels and the Nation's dependency on foreign oil imports.

Geologic storage is the containment of CO_2 in a subsurface formation, so that it will remain safely and permanently stored. Five types of storage are currently under investigation in projects managed by the National Energy Technology Laboratory (NETL), each with unique challenges and opportunities: (1) oil and gas reservoirs, (2) unmineable coal, (3) saline formations, (4) organic-rich shales, and (5) basalt formations. The greatest emissions reductions are achieved when all options for reducing CO_2 emissions are utilized, including energy efficiency, fuel switching, renewable energy sources, and CCUS.

CCUS involves site selection through screening and initial characterization followed by detailed site characterization through tools such as seismic surveys, core analysis, and modeling. Before, during, and after the injection process, monitoring, verification, and accounting efforts focus on the development and deployment of technologies that can provide accurate accounting of stored CO_2 and a high level of confidence that the CO_2 will remain safely and permanently stored. Throughout the CCUS process, risk assessment identifies and quantifies potential health and environmental risks associated with carbon storage and helps to identify appropriate measures to ensure that these risks remain low.

BENEFITS OF CCUS

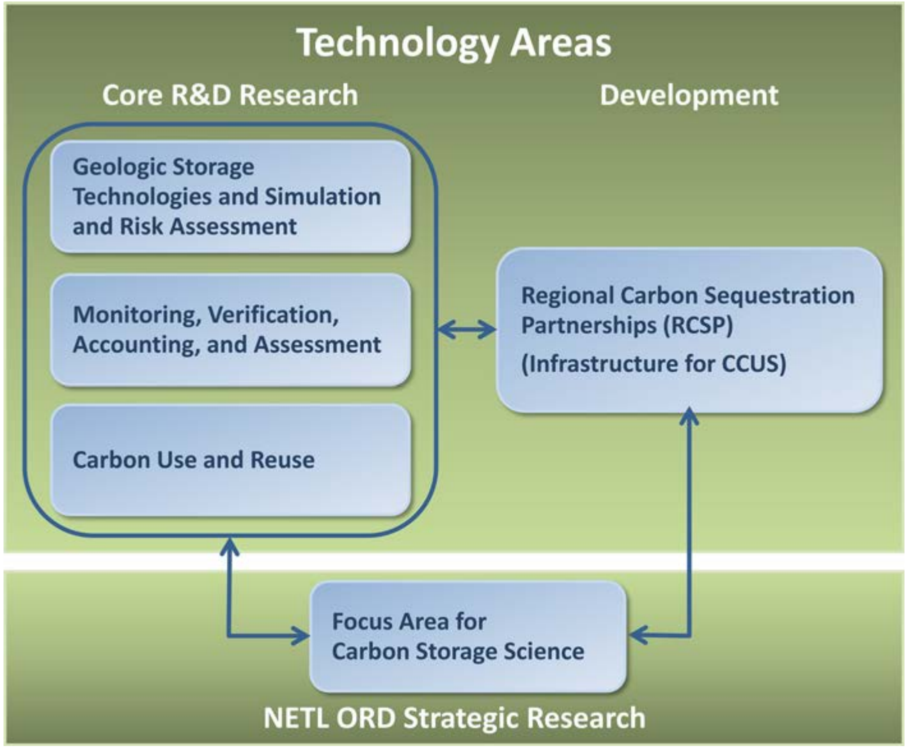
The benefits of CO_2-enhanced oil recovery (EOR) are substantial. NETL estimated that in the United States, 17 billion metric tons of CO_2 would be needed to produce 60 billion barrels of oil by 2100 using next-generation EOR technology. Storage technologies would be necessary to ensure permanent storage and account for this CO_2.

The overall objective of DOE's Carbon Storage Program is to develop and advance CCUS technologies that will significantly improve the effectiveness of the technology, reduce the cost of implementation, and be ready for widespread commercial deployment in the 2025–2035 timeframe. To accomplish widespread deployment, four program goals have been established:

- Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
- Develop and validate technologies to measure and account for 99 percent of injected CO_2 in the injection zones.
- Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.
- Develop best practice manuals for site selection, characterization, site operations, and closure practices.

DOE's Carbon Storage Program

Significant advances have been made in the development of CCUS technologies since DOE launched the Carbon Storage Program. Managed within DOE's Office of Fossil Energy and implemented by NETL, the Carbon Storage Program works to develop effective and economically viable technology options for CCUS. To accomplish this, the Carbon Storage Program focuses on developing technologies to store CO_2 to reduce greenhouse gas emissions from energy producers and other industries without adversely affecting the energy supply or hindering economic growth.



The technology areas that comprise DOE's Carbon Storage Program are shown in the figure at right. Three technology areas form the Core R&D Research, which is driven by the technology needs of industry and others. The technology area that includes the Regional Carbon Sequestration Partnerships (RCSP) and other small- and large-volume field projects, where validation of various CCUS technology options and their efficacy are being confirmed, is developing the infrastructure necessary for the deployment of CCUS. The Carbon Storage infrastructure element tests new technologies and benefits from specific solutions developed in the Core R&D element. In turn, data gaps and lessons learned from large-scale demonstrations are fed back to the Core R&D element to guide future research and development.

These four main technology areas sponsor early applied research at laboratory scale, validate promising technologies at pilot scale, and support large-scale, large-volume injection field projects at pre-commercial scale to confirm system performance and economic viability.

The United States views international engagement as a means to complement the Carbon Storage Program's approach to responding to climate change. Accordingly, DOE is partnering with several international organizations, such as the International Energy Agency's Greenhouse Gas R&D Program, the Carbon Sequestration Leadership Forum, and the North American Carbon Atlas Partnership. DOE is also directly engaged in a number of large-scale CCUS demonstration projects around the world, spanning five continents.

The Carbon Storage Program also supports the development of best practices for CCUS that will benefit projects implementing CCUS at a commercial scale. In general, DOE-applied research is being leveraged with field projects. DOE has established the following plan to ensure that the goal of developing these technologies is met:

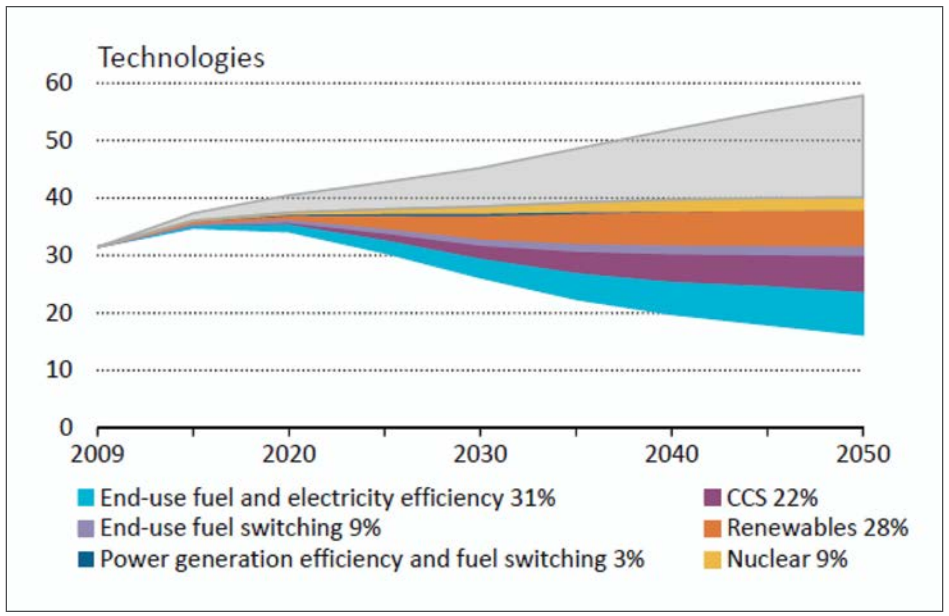
- Manage Core R&D activities within specific technology areas where separate research pathways to develop essential second generation and transformational technologies are identified.
- Utilize the RCSP Initiative to develop future infrastructure, as well as validate and field-test technologies through all stages leading to commercialization.
- Engage a wide variety of industries; federal, state, and local government agencies; academia; and environmental organizations.
- Work with NETL's Office of Program Planning and Analysis to determine the benefits of research and establish a systems approach to confirm that technologies are capable of meeting Carbon Storage Program goals.

Why Perform Carbon Storage?

Greenhouse gases in the atmosphere contribute to the greenhouse effect, which is the trapping of radiant heat from the sun in the Earth's atmosphere. One greenhouse gas of particular interest is CO_2 because it is one of the most prevalent greenhouse gases. Carbon dioxide is a colorless, odorless, nonflammable gas that provides a basis for the synthesis of organic compounds essential for life. Atmospheric CO_2 originates from both natural and manmade sources. Natural sources of CO_2 include volcanic outgassing, the combustion and decay of organic matter, and respiration. Manmade, or anthropogenic, sources of CO_2 are produced from the burning of various fossil fuels for power generation and transportation, as well as industrial activities.

The greenhouse effect is a natural and important process in the Earth's atmosphere. However, greenhouse gas levels have significantly increased above pre-industrial levels. According to the Energy Information Administration, annual global energy-related CO_2 emissions have reached approximately 32 billion metric tons (approximately 36 billion tons). Many scientists consider this increase in atmospheric greenhouse gases to be a contributing factor to global climate change.

CCUS promises to provide a significant reduction in greenhouse gas emissions. Conservation, renewable energy, and improvements in the efficiency of power plants, automobiles, and other energy consuming devices are also important steps that must be taken to mitigate greenhouse gas emissions. No single approach is sufficient to stabilize the concentration of greenhouse gases in the atmosphere, especially when the growing global demand for energy and the associated potential increase in greenhouse gas emissions is considered. Technological approaches that are effective in reducing atmospheric greenhouse gas concentrations, while, at the same time, allow economic growth and prosperity associated with energy use, are needed. The International Energy Agency has identified carbon capture and storage (CCS) as a significant technology option necessary to stabilize greenhouse gas concentrations in the atmosphere. In 2012, they identified CCS as contributing to at least 22 percent of the necessary reductions from industrial and power sources.

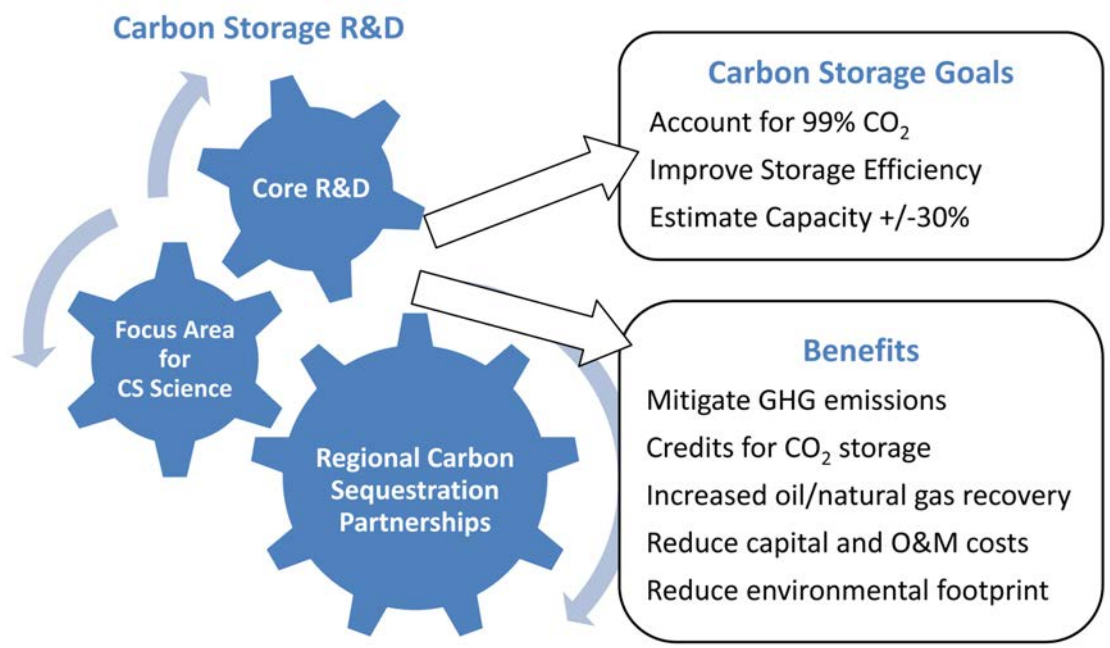


Technology options to stabilize greenhouse gas concentrations in the atmosphere.
(Reference: OECD/IEA 2012 Energy Technology Perspectives)

Economic, Technical, and Environmental Benefits

Significant benefits can be achieved through carbon storage and will be realized as the Carbon Storage Program achieves its goals. The deployment of the technologies developed and validated by the Carbon Storage Program will save hundreds of billions of dollars due to societal benefits of reducing greenhouse gas emissions to the atmosphere; monetized credits for CO_2 permanently stored in deep geologic formations; production of additional domestic oil and gas resources during recovery operations; reduced operational and maintenance costs of storage facilities; and the savings realized by reducing the environmental footprint of storage facilities by optimizing reservoir efficiency. The technologies developed by the program are considered enabling technologies because they will allow industry to cost effectively develop projects, comply with existing regulations for carbon storage projects, and validate that CO_2 has been permanently stored. The figure below illustrates the R&D efforts, goals, and possible benefits derived from the R&D that the Carbon Storage Program supports.

Many of the technologies being developed by the Carbon Storage Program to address various facets of carbon storage have the potential to reduce storage costs. The cost reductions achieved by the Carbon Storage Program could make mitigation of CO_2 emissions from the power sector more cost-effective relative to other alternatives. This serves to keep the cost of electricity low, and provides an economic benefit in terms of maintaining income levels for energy consumers; increasing direct, indirect, and induced employment from the CCUS infrastructure build out; positively impacting gross domestic product; and avoiding social costs due to successful mitigation of CO_2 emissions.

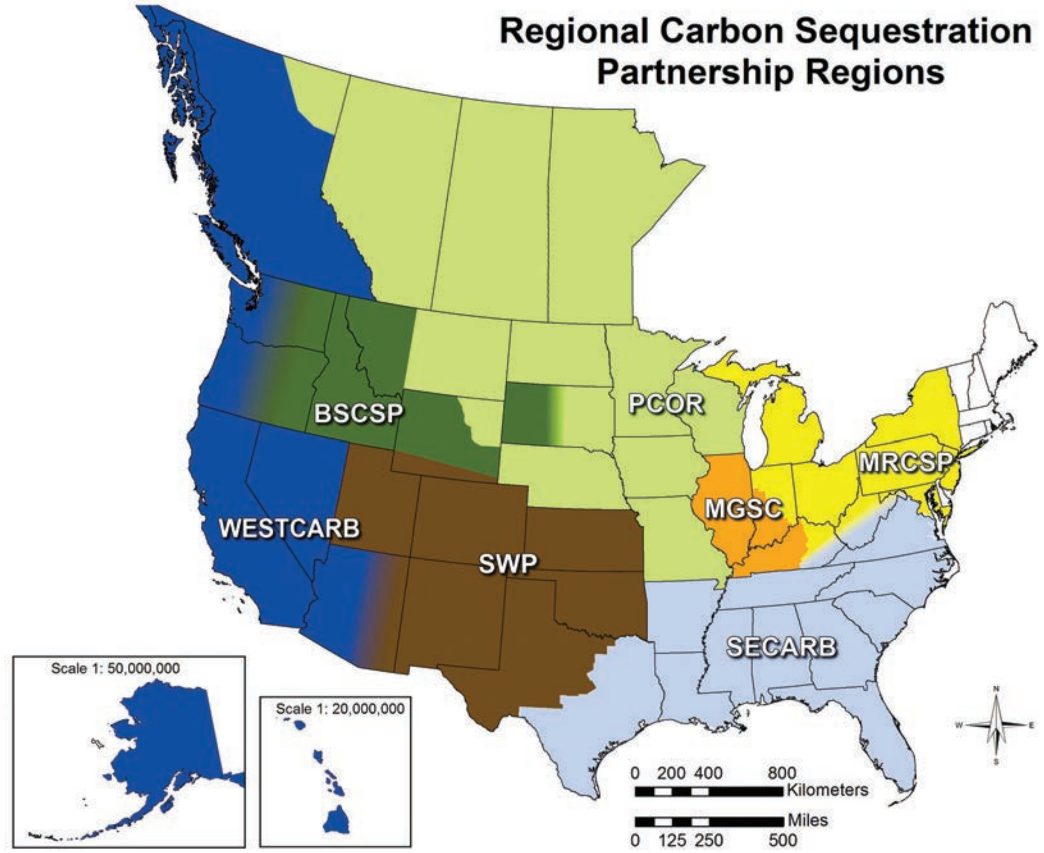


Schematic of Carbon Storage Program RD&D Efforts, Goals, and Possible Benefits of the R&D.

DOE's Regional Carbon Sequestration Partnerships

DOE determined early in the program's development that addressing CO_2 mitigation from power and industrial sources regionally would be the most effective way to address differences in geology, climate, population density, infrastructure (human capital), and socioeconomic development throughout the United States.

DOE has created a network of seven Regional Carbon Sequestration Partnerships (RCSPs) to help develop the technology and infrastructure needed to implement large-scale CO_2 storage in different regions and geologic formations. The RCSPs are public/private partnerships comprising more than 400 organizations over 43 states and four Canadian provinces. The RCSPs include representatives from state and local agencies, regional universities, national laboratories, non-government organizations, foreign government agencies, engineering and research firms, electric utilities, oil and gas companies, and other industrial partners. The diversity of partners is important to the success and deployment of CCUS. Each of the RCSPs are led by one organization that manages the partnership's activities, including characterization efforts, planning and leading small- and large-scale injection tests, and integrating the results. In addition to efforts to implement small- and large-scale field projects, the RCSPs also work to develop human capital, encourage stakeholder networking, support regulatory policy development, develop carbon mitigation plans, and enhance public outreach and education regarding CCUS.



The RCSPs' technology area research effort is conducting regional characterization and small- and large-scale field projects to demonstrate that different types of geologic storage reservoirs, distributed over different geographic regions, have the capability to permanently store CO_2, and provide the basis for commercial-scale CO_2 tests. Regional Carbon Sequestration Partnerships' field projects involve integrated system testing and validation of geologic storage; simulation and risk assessment; and monitoring, verification, and accounting technologies in different depositional environments.

Through these small- and large-scale injection projects, the Carbon Storage Program is demonstrating adequate injectivity, available storage resource and capacity, and storage permanence across the range of storage types, as well as to develop injection strategies, risk assessment, and monitoring strategies that are best suited for the particular geologic structure, reservoir architecture, and range of properties characteristic of each of 11 major depositional classes. Knowledge and experience gained from small- and large-scale field projects in different depositional environments will determine the systems best suited for geologic storage on a regional basis. Small- and large-scale field projects provide understanding of the impacts of different depositional systems on flow, injectivity, containment, and capacity and validate simulation models used to assess design and performance.

The RCSP Initiative is being implemented in the following three phases:

- **Characterization Activities:** Initial characterization of each region's potential to store CO_2 in different geologic formations.
- **Small-Scale Field Projects:** Validation of the most promising regional storage opportunities through a series of small-scale field projects.
- **Large-Scale Field Projects:** Implementation of large-scale field testing involving at least 1 million metric tons of CO_2 per project to confirm that CO_2 injection and storage can be achieved safely, permanently, and economically.

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

DOE's Regional Carbon Sequestration Partnerships' Small-Scale CO_2 Injection Projects

DOE's Carbon Storage Program includes 23 small-scale CO_2 injection (typically less than 500,000 metric tons total) projects. The RCSPs' efforts were augmented by three additional sites in 2011. The RCSPs' small-scale field projects focus on validating the most promising regional opportunities to deploy CCUS technologies by building upon the accomplishments of the characterization activities. Efforts during the small-scale field projects are being conducted to:

- Validate and refine current reservoir simulations for CO_2 storage projects.
- Collect physical data to confirm CO_2 storage potential and injectivity estimates.
- Demonstrate the effectiveness of monitoring, verification, and accounting technologies.
- Develop guidelines for well completion, operations, and abandonment.
- Develop strategies to optimize the CO_2 storage potential of various geologic formations.

Geologic field projects targeted four geologic storage types—saline formations, oil and gas reservoirs, unmineable coal, and basalt formations. The completed tests have provided valuable information to better understand CO_2 storage potential in different geologic settings across the United States and determine specific areas that require future research. The small-scale field projects also included terrestrial carbon storage sites.

SMALL-SCALE TESTS IN CLASTIC AND CARBONATE FORMATIONS CONTAINING SALINE WATERS

Small-scale field projects were performed in saline formations across multiple depositional environments. Saline formations targeted for geologic storage are porous sedimentary deposits saturated with brine having salinity greater than 10,000 milligrams per liter (mg/l) total dissolved solids. The six field projects injected a total of more than 63,000 metric tons of CO_2 with test results indicating that these formations can accept and safely store CO_2.

SMALL-SCALE TESTS IN CLASTIC AND CARBONATE FORMATIONS CONTAINING OIL AND GAS

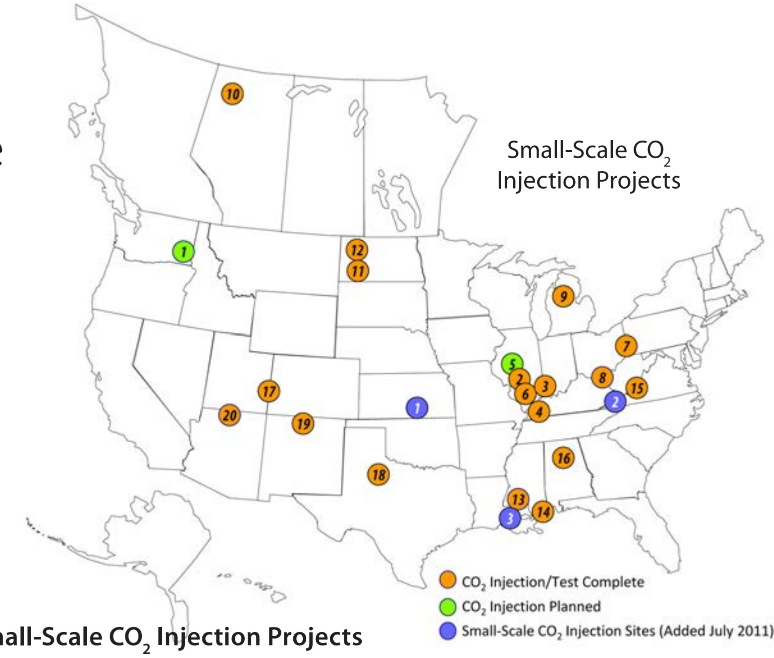
The RCSPs have conducted small-scale tests in oil and gas reservoirs across multiple types of depositional environments. Oil and gas reservoirs offer significant near-term potential for CO_2 storage as they have held crude oil and natural gas for millions of years and are typically well studied due to oil and gas exploration. A total of more than 1.4 million metric tons of CO_2 were safely injected during these validation tests. Research results indicate the ability of the reservoirs to accept and safely store injected CO_2 while potentially increasing hydrocarbon production.

UNMINEABLE COAL TESTS

Unmineable coal seams are too deep or too thin to be economically recovered. However, these formations can be developed for their ability to both produce methane and store CO_2. Five small-scale tests injected a combined volume of more than 18,000 metric tons of CO_2 into coal seams to study their storage capability. Test results showed adequate CO_2 containment capabilities for the geologic sealing layers located above the injected formations. The small-scale tests are focused on addressing challenges to CO_2 storage in unmineable coal seams to move toward commercialization of this technology.

BASALT FORMATION TESTS

Basalt is a volcanic rock with a unique chemical makeup that could potentially convert injected CO_2 to a solid mineral form, thus isolating it from the atmosphere permanently. This, combined with basalt's tendency to be porous and fractured, makes these formations potential candidates for CO_2 storage. The Big Sky Carbon Sequestration Partnership is the only RCSP investigating basalts by conducting an injection of approximately 1,000 metric tons of CO_2.



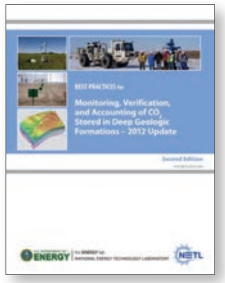
Small-Scale CO_2 Injection Projects

	Project Name	Project Type	Injection Formation(s) (Reservoir)	Planned or Actual CO_2 Injected (metric tons total) April 2012
1	Wallula Basalt Pilot Study	Basalt	Interflow zones, Grande Ronde Basalt	None
2	Loudon Single Well Huff 'n' Puff Project	HNP	Cypress & Mississippi Weiler SS	39
3	Mumford Hills Project	EOR	Clore Sandstone	6,560
4	Sugar Creek Project	EOR	Jackson Sandstone	6,300
6	Tanquary Well Project	ECBM	Springfield Coal	91
7	Appalachian Basin Geologic Test at R.E. Burger Power Plant: Fegenco Well	Saline	Clinton SS/Salina Fm/Oriskany SS	50
8	Duke Energy - East Bend Well Site	Saline	Mt Simon	1,000
9	Michigan Basin Geologic Test	Saline	Bass Islands Dolomite	60,000
10	Zama Acid Gas EOR, CO_2 Storage, and Monitoring Project	EOR	Middle Devonian Keg River Formation	80,000 acid gas
11	NW McGregor EOR HNP Project	EOR / HNP	Mission Canyon Limestone	400
12	Lignite CCS Project	ECBM	Lignite Seams in Ft. Union Formation	80
13	Gulf Coast Stacked Storage Project	EOR	Tuscaloosa Formation	627,744
14	Plant Daniel Project	Saline	Massive Sand, Lower Tuscaloosa	2,740
15	Central Appalachian Basin Coal Test	ECBM	Pocahontas & Lee Formation	907
16	Black Warrior Project	ECBM	Pottsville Formation (coal zones)	252
17	Aneth EOR Sequestration Test	EOR	Desert Creek & Ismay Formation	630,000
18	SACROC CO_2 Injection Project	EOR	Horseshoe Atoll & Pennsylvanian Reef/ Bank Play	86,000
19	Pump Canyon CO_2- ECBM/Sequestration Demonstration	ECBM	Fruitland Coal Formation	16,700
20	Arizona Utilities CO_2 Storage Pilot	Saline	Martin & Naco Formations	None
—	Northern California Geologic Characterization	Geologic Characterization	Domengine, Mokelumne River, H&T/ Starkey SS	None
1	University of Kansas Center for Research, Inc.	Multiple Formations	Arbuckle	70,000
2	Virginia Polytechnic Institute and State University	ECBM	Appalachian Basin; Sourwood or Oakwood CBM fields	20,000
3	Blackhorse Energy, LLC	EOR	Gulf Coast Basin; First Wilcox Sand	53,000

* 5 MGSC's Project #5 (Illinois Basin) was changed to a large-scale injection.

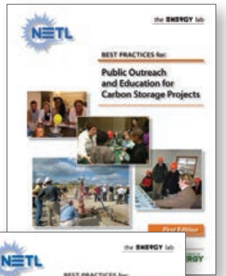
DOE's CCUS Best Practice Manuals

Developing best practices—or reliable and consistent standards and operational characteristics for CO_2 collection, injection, and storage—is essential for providing the basis for a legal and regulatory framework and encouraging widespread global CCUS deployment. The lessons learned during the RCSPs' small-scale field projects are being used to generate a series of best practice manuals (BPMs) that serve as the basis for the design and implementation of both large-scale field projects and commercial CCUS projects. NETL's BPMs are available via the Carbon Storage Reference Shelf at: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/refshelf.html.



NETL has released the following BPMs:

- "Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations" provides an overview of monitoring, verification, and assessment techniques that are currently in use or being developed; summarizes DOE's monitoring, verification, and accounting R&D program; and presents information that can be used by regulatory organizations, project developers, and policymakers to ensure the safety and efficacy of carbon storage projects. NETL released the second edition of this BPM in October 2012.



- "Public Outreach and Education for Carbon Storage Projects" is intended to assist project developers in understanding and applying best outreach practices for siting and operating CO_2 storage projects. This manual provides practical, experience-based guidance on designing and conducting effective public outreach activities.

- "Geologic Storage Formation Classification: Understanding Its Importance and Impacts on CCS Opportunities in the United States" is intended to aid individuals in understanding the characteristics of geologic formations that could potentially be used for CCUS and predict the behavior of CO_2 within those environments.

- "Site Screening, Selection, and Characterization for Storage of CO_2 in Deep Geologic Formations" establishes a framework and methodology for proper site screening, selection, and initial characterization of geologic storage sites that: (1) provides stakeholders with a compilation of best practices for site screening, selection, and characterization; (2) communicates the experience gained through DOE's RCSPs; and (3) develops a consistent, industry-standard framework, terminology, and set of guidelines for project-related storage capacity and potential risk estimates.

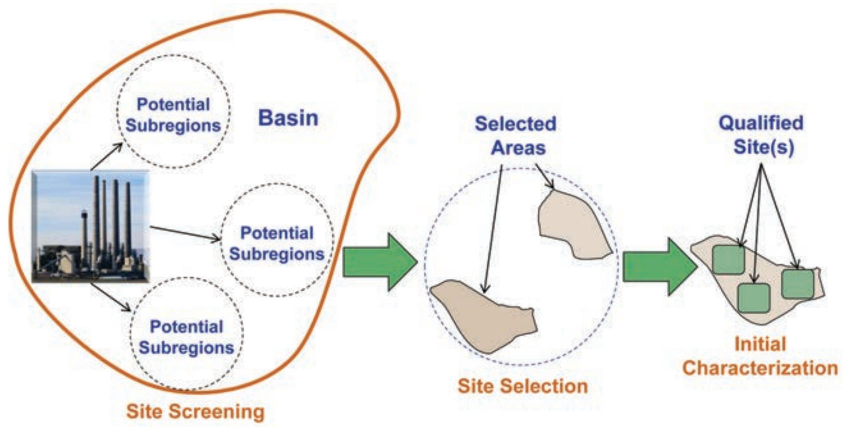
- "Risk Analysis and Simulation for Geologic Storage of CO_2" illustrates the concepts of risk analysis (risk assessment) and numerical simulation by examining the experience gained by DOE's RCSPs while conducting multiple field projects. This BPM focuses on the risks arising from unplanned migration of injected CO_2 from the confining zone and the ways in which the RCSPs have used codes to model the specific processes (thermal and hydrologic, chemical, mechanical, and biologic) in the subsurface that must be considered when modeling the behavior of injected CO_2.

- "Carbon Storage Systems and Well Management Activities" covers the planning, permitting, design, drilling, implementation, and decommissioning of CO_2 storage wells. The manual provides an overview of the well-management activities typically associated with CCUS projects, beginning with pre-injection planning and continuing through post-injection operations. It provides a roadmap and resource for lessons learned about well-management issues and what project planners and operators can expect as a project unfolds.

- "Terrestrial Sequestration of Carbon Dioxide" details the most suitable operational approaches and techniques for terrestrial storage—a CO_2 mitigation strategy capable of removing CO_2 already in the air by enhancing the storage capability of soils, grazing and crop lands, and trees.

Site Characterization for Geologic Storage Sites

The process of identifying suitable geologic storage sites involves a methodical and careful analysis of both technical and non-technical aspects of potential sites. This process is analogous to the methods used in the petroleum industry to advance a project through a framework of resource classes and project status subclasses until the project produces hydrocarbons. The proposed framework would contain three distinct phases of evaluation (Exploration Phase, Site Characterization Phase, and Implementation Phase) corresponding to each resource class and further subdivided into project subclasses.

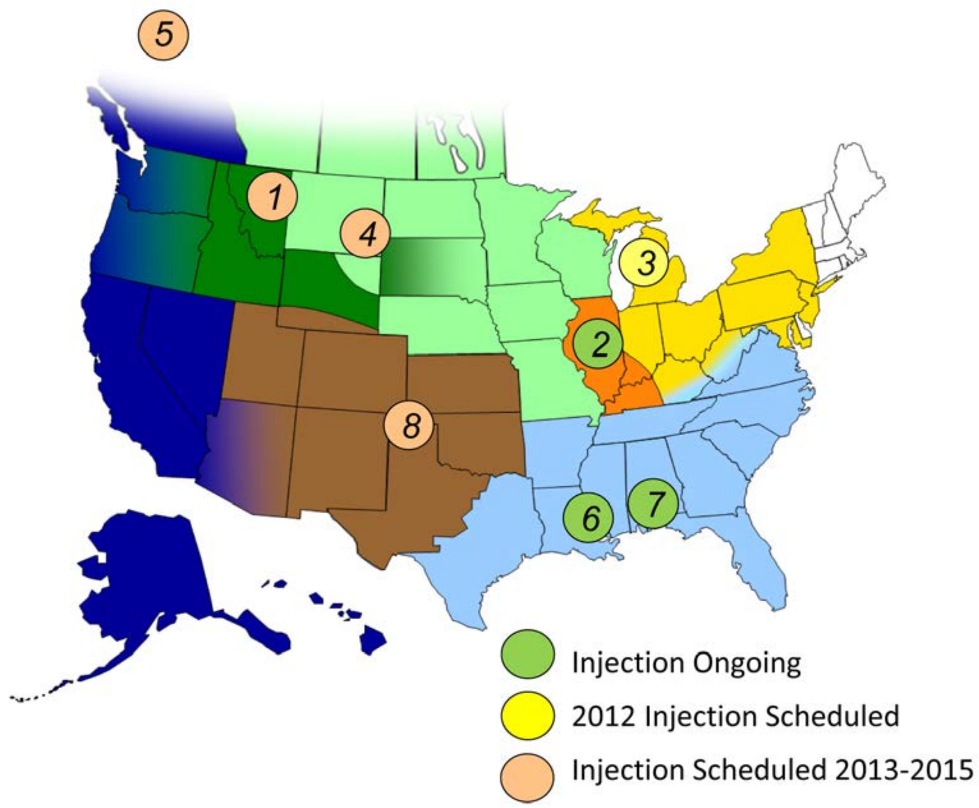


Graphical Representation of "Project Site Maturation" through the Exploration Phase.

Atlas IV CO_2 Geologic Storage Resource Estimates

Carbon dioxide geologic storage information in *Atlas IV* was developed to provide a high-level overview of CO_2 geologic storage potential. Areal extents of geologic formations and CO_2 resource estimates presented are intended to be used as an initial assessment of potential geologic storage.

DOE's Regional Carbon Sequestration Partnerships' Large-Scale CO_2 Injection Projects



Note: Some locations presented on map may differ from final injection location.

Large-Scale CO_2 Injection Projects

	RCSP	Geologic Province	Target Injection Volume (metric tons)
1	Big Sky	Kevin Dome - Nugget Sandstone	1,000,000
2	MGSC	Illinois Basin – Mt. Simon Sandstone	1,000,000
3	MRCSP	Michigan Basin – Niagaran Reef	1,000,000
4	PCOR	Powder River Basin – Bell Creek field	1,500,000
5		Horn River Basin – Carbonates	2,000,000
6	SECARB	Gulf Coast – Cranfield field – Tuscaloosa Formation	3,400,000
7		Gulf Coast – Paluxy Formation	200,000
8	SWP	Regional CCUS Opportunity	1,000,000
	WESTCARB	Regional Characterization	

The RCSPs large-scale injection projects build on the findings from the characterization activities and small-scale field projects. These large-scale projects involve the injection of 1 million metric tons or more of CO_2 into regionally significant geologic formations of different depositional environments. These large-volume injection tests are designed to demonstrate that CO_2 storage sites have the potential to store regional CO_2 emissions safely, permanently, and economically for hundreds of years. Carbon dioxide sources include natural deposits, ethanol facilities, natural gas processing plants, and capture from power plants. Large-scale projects will contribute to a better understanding of technical and non-technical aspects for commercial-scale CCUS projects, including regulatory, liability, and ownerships issues associated with these projects, and will provide a firm foundation for commercialization of large-scale CCUS.

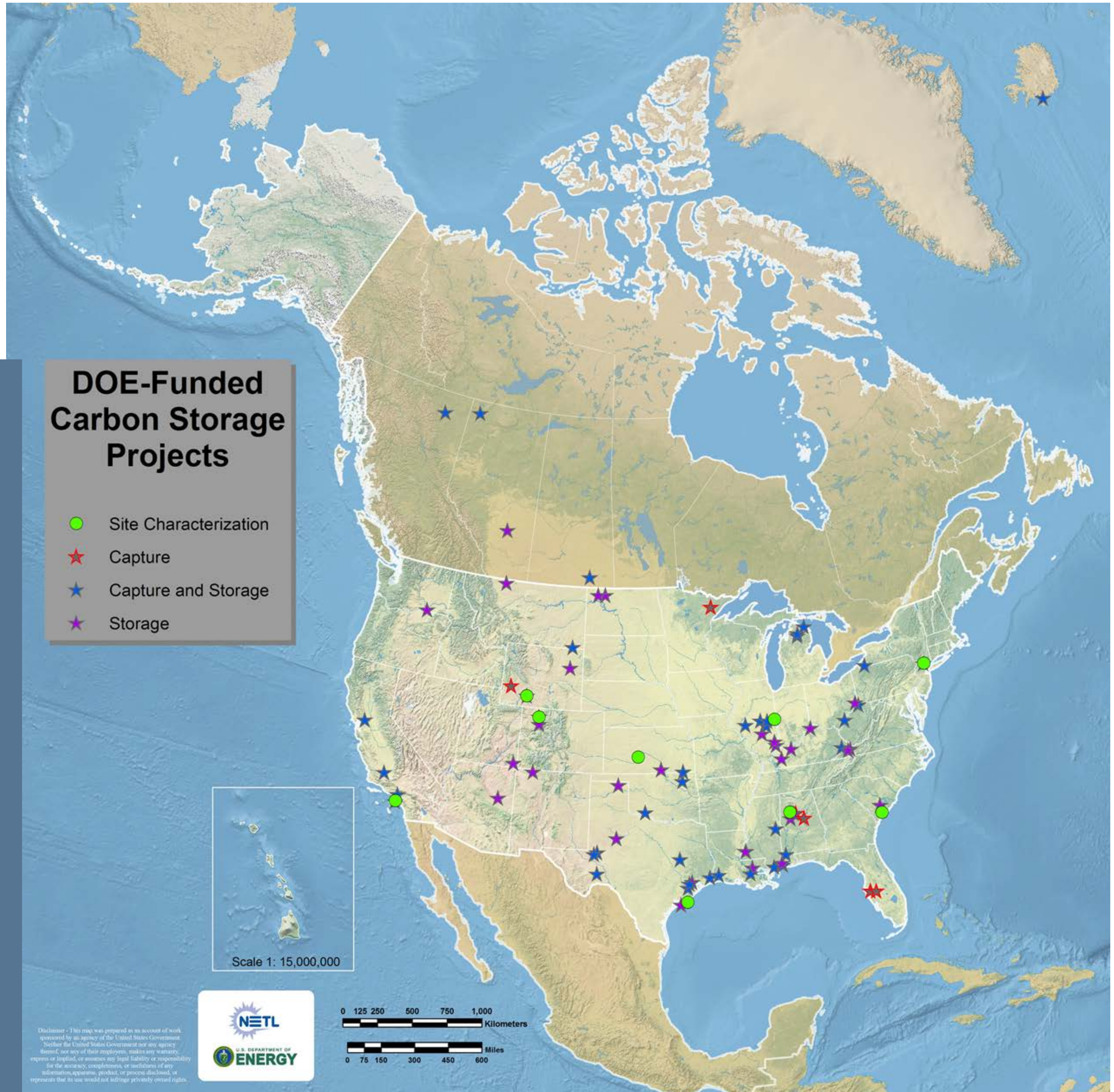
Many of these projects are primarily focused on storage during EOR operations. One such example is being conducted by the Plains CO_2 Reduction Partnership, which is performing large-scale injection into an oil-bearing formation, in this case, the Williston Basin. Other projects are focused on injection into saline-bearing formations. Saline-bearing formations targeted for geologic storage are porous sedimentary formations (clastic and carbonate) saturated with brine having salinity greater than 10,000 mg/l total dissolved solids. The formations and their ability to accept and store CO_2 vary significantly based on their depositional environment, porosity, permeability, and chemical/physical characteristics of the formation.

The large-scale field projects are implemented in 3 stages: site characterization, operations, and closure phases. Results obtained from these large-scale injection tests will provide the foundation for validating that CCUS technologies can be commercially deployed throughout the United States. These large-scale projects are necessary to validate storage projects integrated with carbon capture technologies from various CO_2 sources and all storage types in multiple basins throughout the United States and parts of Canada.

As of October 2012, injection has occurred at three large-scale injection field sites. Within the Southeast Regional Carbon Sequestration Partnership, CO_2 injection for the Early Test at Denbury's Cranfield location near Natchez, Mississippi, followed a small-scale injection at the same location, began in April 2009. As of August 2012, approximately 3.3 million metric tons have been stored in the down-dip water leg of the lower Tuscaloosa Formation, which is approximately 10,000 feet below ground surface. Also within the Southeast Regional Carbon Sequestration Partnership, CO_2 injection for the Anthropogenic Test at Denbury's Citronelle field, located just north of Mobile, Alabama, began in September 2012 with storage in the Paluxy Formation (saline) at 9,400 feet below ground surface. In the Midwest Geological Sequestration Consortium,

CO_2 injection began in November 2011 in Decatur, Illinois. Injection has been ongoing at an average rate of 1,000 metric tons of CO_2 per day into the lower Mount Simon Sandstone at a depth of approximately 7,000 feet. As of publication, more than 300,000 metric tons of CO_2 have been injected at the Archer Daniels Midland site.

A wide variety of carbon storage projects are being conducted through multiple DOE programs to validate that CCUS is feasible at a commercial-scale.



In order to validate that CCUS can be conducted at a commercial scale, each of the large-scale projects are pursuing a number of key goals:

- Demonstrate adequate injectivity and available capacity at near-commercial scale by injecting CO_2 over an extended period of time.
- Verify storage permanence by validating that CO_2 will be contained in the target formations; develop technologies and protocols to quantify potential releases and ensure that the projects do not adversely impact underground sources of drinking water (USDWs) or cause CO_2 to be released to the atmosphere.
- Determine the areal extent of the CO_2 plume and potential release pathways by monitoring the areal extent and vertical migration of the CO_2 during and after project completion; develop methodologies to determine the presence of release pathways such that the proposed mitigation strategy can sustain a near-zero release.
- Develop risk assessment strategies by indentifying risk parameters, probability and potential impact of occurrence, and mitigation strategies.
- Engage in public outreach and education about CCUS.
- Develop information that supports the development of an effective regulatory and legal framework for safe, long-term injection and geologic CO_2 storage in the regions that the projects are developed.

DOE's Global CCUS Collaborations

DOE's global work includes ongoing collaborations with numerous 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 International Energy Agency Greenhouse Gas R&D Program, Global Carbon Capture and Storage Institute, Carbon Sequestration Leadership Forum, North American Carbon Atlas Partnership, and U.S.-China Clean Energy Research Center. Supporting these projects directly benefits U.S. efforts to develop technologies and tools to meet the strategic goals of the program. In addition, these collaborations also encourage technical transfer of the lessons learned between industry and academia to facilitate the adoption of these technologies in the field and to train personnel in the United States for future careers in the CCUS industry throughout the world.

DOE Support to International CCUS Projects	
1	DOE is a lead sponsor and U.S. scientists test multiple monitoring and simulation technologies.
2	Supporting the Plains CO_2 Reduction Partnership to conduct monitoring and reservoir modeling of CO_2 injection into pinnacle reefs.
3	Supporting Plains CO_2 Reduction Partnership to conduct monitoring and reservoir modeling studies.
4	Supporting Indiana University to perform reservoir simulations, and recently supported the Scripps Institute of Oceanography to conduct time-lapse gravity surveys.
5	Supporting the Lawrence Livermore National Laboratory to simulate geomechanical conditions of the reservoir and caprock.
6	Supported Lawrence Berkeley National Laboratory to deploy downhole monitoring technology based on thermal perturbation sensors.
7	Supporting Columbia University Lamont-Doherty Earth Observatory to test tracer methods to assess trapping mechanisms in basalt formations.
8	Supporting the Lawrence Livermore National Laboratory and Lawrence Berkeley National Laboratory to test field and remote sensing monitoring technologies and modeling geomechanical and geochemical reservoir processes.
9	Supporting scientists at Lawrence Berkeley National Laboratory to test multiple monitoring technologies at depleted gas field and saline formations.
10	Supporting West Virginia University and Lawrence Livermore National Laboratory to assess capacity for storage, and simulating hydrogeologic and geochemical reservoir conditions.

International Demonstrations

DOE is partnering with many international organizations to advance research in carbon storage. These projects are operating throughout the world. Benefits of U.S. scientists' participation range from opportunities to field project innovative technologies at commercial- and large-scale CCUS operations around the world, to representing U.S. expertise on multinational CCUS investigative R&D teams.

Carbon Sequestration Leadership Forum

The Carbon Sequestration Leadership Forum is a ministerial-level organization focused on developing improved, cost-effective technologies for the separation and capture of CO_2 for transport and safe, long-term storage. An important Carbon Sequestration Leadership Forum goal is to improve CCUS technologies through coordinated R&D with international partners and private industry. DOE continues to maintain a leadership role in the Carbon Sequestration Leadership Forum.

North American Carbon Atlas Partnership

The North American Carbon Atlas Partnership is one of the key efforts of the North American Energy Working Group and is a joint CO_2 mapping initiative involving the United States, Canada, and Mexico. Please see page 14 for more information.

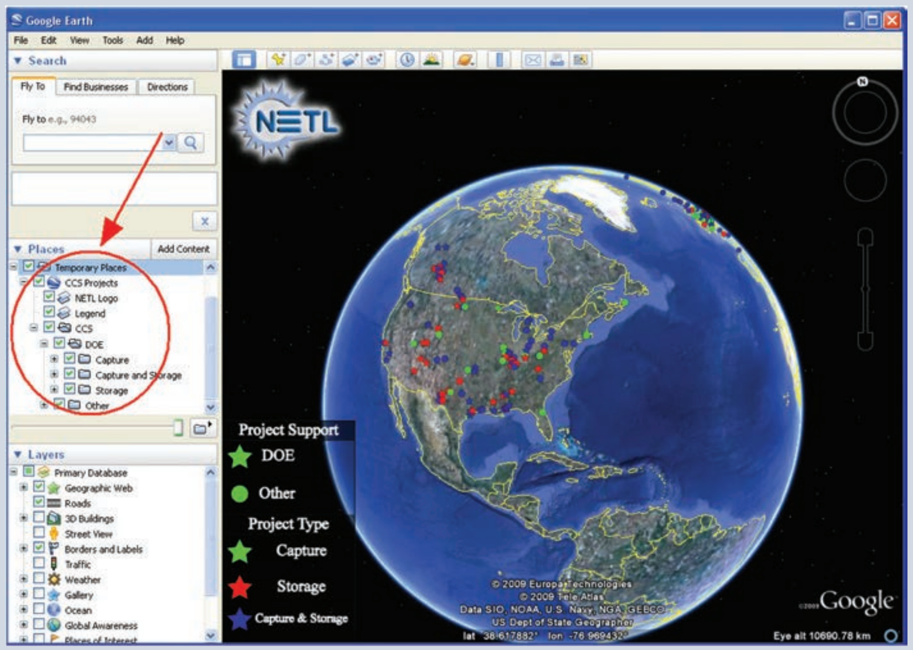
Other International Activities

In addition to supporting the international organizations and projects in which DOE participates to advance international CCUS efforts, DOE works closely with the International Energy Agency Greenhouse Gas R&D Program, International Energy Agency, and North American partners through trilateral and bilateral agreements on energy with Canada and Mexico. The International Energy Agency Greenhouse Gas R&D Program is a multilateral organization that promotes energy security, economic development, and environmental protection throughout the world. The International Energy Agency Greenhouse Gas R&D Program experts have endorsed the efforts of DOE's RCSPs and their large-scale projects as a successful approach to advance CCUS in the United States, Canada, and internationally. These endorsements resulted from extensive peer reviews of the program conducted in 2008 and 2011.

DOE directly supported the development of projects through these organizations and promotes the transfer of technologies from the core R&D and lessons learned from the RCSPs to support global deployment of CCUS technologies. DOE/NETL believes that the economic rewards achieved through new business opportunities in the United States and abroad will encourage other countries to engage in CO_2 storage projects.

NETL's CCUS DATABASE

NETL's CCUS Database includes active, completed, proposed, potential, or 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 publicly 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. As of mid-2012, the database contained 254 CCUS projects worldwide. The 254 projects include 65 capture, 61 storage, and 128 for capture and storage in more than 27 countries across 6 continents. While most of the projects are still in the planning and development stage, or have recently been proposed, 20 are actively capturing and injecting CO_2.



The NETL CCUS database is a layer in Google Earth and is available at: http://www.netl.doe.gov/technologies/carbon_seq/global/database/index.html.

DOE's Interagency CCUS Collaborations

The Carbon Storage Program team has worked with different federal and state agencies to help inform regulatory issues for wide-scale deployment of CCUS technologies. This includes interacting with the U.S. Environmental Protection Agency (EPA), the U.S. Department of Interior's Bureau of Ocean Energy Management, the U.S. Department of Interior's Bureau of Land Management and U.S. Geological Survey, the Interstate Oil and Gas Compact Commission, the Ground Water Protection Council, and the U.S. Department of Transportation on issues related to CO_2 storage and transport. The objective of these efforts is to provide research results that help inform regulatory decision making. The methodologies developed and data collected by the program also support the efforts to determine the potential role federal lands might play in developing CCUS opportunities onshore and offshore.

With regard to CO_2 storage, activities with these agencies include: participating in the U.S. EPA's CCS Working Group, participating in the preparation of several Bureau of Land Management reports to Congress, assisting the Bureau of Ocean Energy Management with developing rules for offshore CO_2 injection, examining the legal and regulatory framework for CO_2 storage with the Interstate Oil and Gas Compact Commission, and examining state regulatory program data management for CO_2 storage with the Ground Water Protection Council. The Carbon Storage Program team has collaborated with the U.S. Department of Transportation, the Federal Energy Regulatory Commission, the National Association of Regulatory Utility Commissioners, and the Surface Transportation Board to examine the regulatory framework for CO_2 pipeline siting, operation, and tariffs. The program has also participated in the Interstate Oil and Gas Compact Commission Pipeline Transportation Taskforce on CO_2 pipelines for carbon storage. All of this involves more than 20 states and Canadian provinces that are members of the Interstate Oil and Gas Compact Commission.

Interagency Task Force on Carbon Capture and Storage

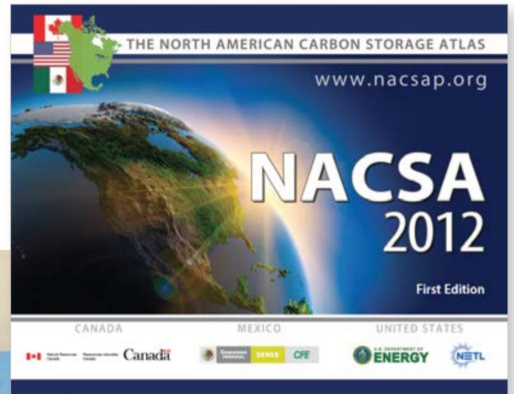
In February 2010, 14 Executive Departments and federal agencies established an Interagency Task Force on Carbon Capture and Storage. On August 12, 2010, the Task Force delivered a series of recommendations on overcoming the barriers to widespread, cost-effective deployment of CCS within 10 years. The report concluded that CCS can play an important role in domestic greenhouse gas emissions reductions while preserving the option of using abundant domestic energy resources. However, widespread, cost-effective deployment of CCS will occur only if the technology is commercially available at economically competitive prices and supportive national policy frameworks are in place. More information is available at: http://www.fe.doe.gov/programs/sequestration/ccs_task_force.html.

DOE Internal Collaborations – National Risk Assessment Partnership

NETL is leading a multi-lab initiative called the National Risk Assessment Partnership (NRAP) with Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Pacific Northwest National Laboratory. The goal of NRAP is to develop a science-based methodology for calculating risks at any CO_2 storage site while providing necessary scientific and technological advances to support that methodology. The NRAP toolsets will include methodologies and models that predict behavior of each component of the subsurface systems. The NRAP methodology is needed to support the business case for full-scale carbon utilization and storage projects in a wide range of potential locations.

North American Carbon Atlas Partnership

As a part of the North American Energy Working Group, the United States (DOE), Canada (Natural Resources Canada), and Mexico (Secretariat of Energy) have initiated the North American Carbon Atlas Partnership (NACAP). The goal of NACAP is for each country to identify, gather, and share data for CO_2 stationary sources and geologic storage sites. NACAP is a mapping initiative designed to disseminate and exchange CCS-related information between the United States, Canada, and Mexico, and is necessary to effectively speed the development of a CO_2 sources and GIS database in North America. The development of this geographic information system system supports the DOE Office of Fossil Energy's Carbon Storage Program, the objectives of the North American Energy Working Group, 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 serve as a key opportunity to foster collaboration among the three countries in the area of CCS.



Under the NACAP effort, the hardcopy of the North American Carbon Storage Atlas (NACSA) was released in May 2012. An interactive map viewer was also developed with the compiled data to complement the NACSA website.

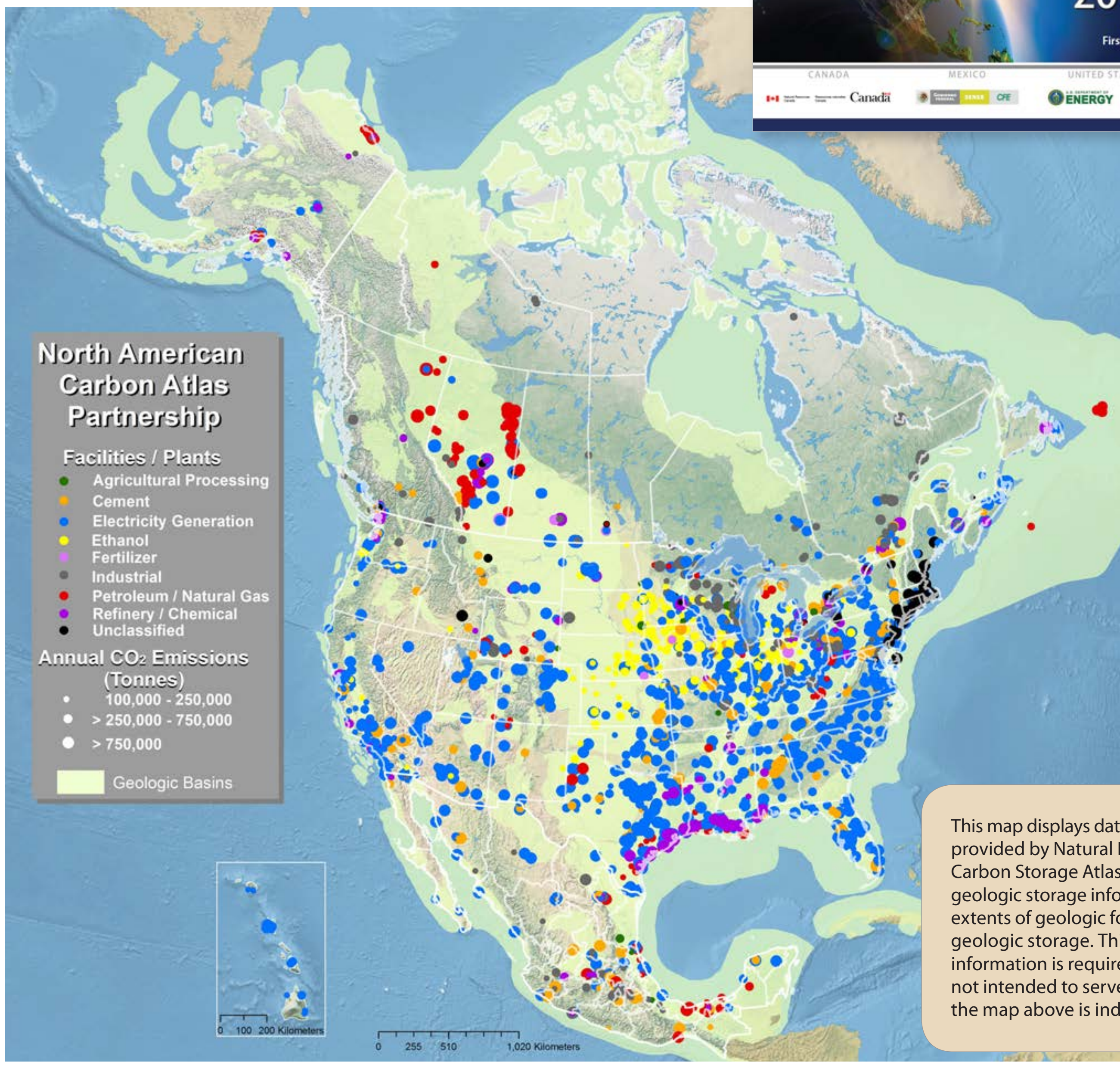
NACSA Website

The NACSA website (http://www.nacsap.org) serves as a resource for the latest information on CO_2 stationary sources and CO_2 storage resources in North America. The website is updated as new information is received and existing data are refined and expanded. The website also houses full storage resource estimation methodologies and links to valuable information from the three countries involved in the NACAP effort.

NACSA Viewer

The NACSA Viewer, accessible from the NACSA website, provides Web-based access to all NACSA data (CO_2 stationary sources, potential geological CO_2 storage resources, etc.) and analytical tools required for addressing CCS deployment. Distributed computing solutions link the three countries' data and other publicly accessible repositories of geologic, geophysical, natural resource, and environmental data.

The NACSA website and NACSA Viewer are hosted by West Virginia University and NETL, respectively. Canadian and Mexican data are uploaded when new information becomes available. U.S. data are made available in real time from NATCARB, which in turn receives its data from the seven RCSPs and from specialized data warehouses and public servers.



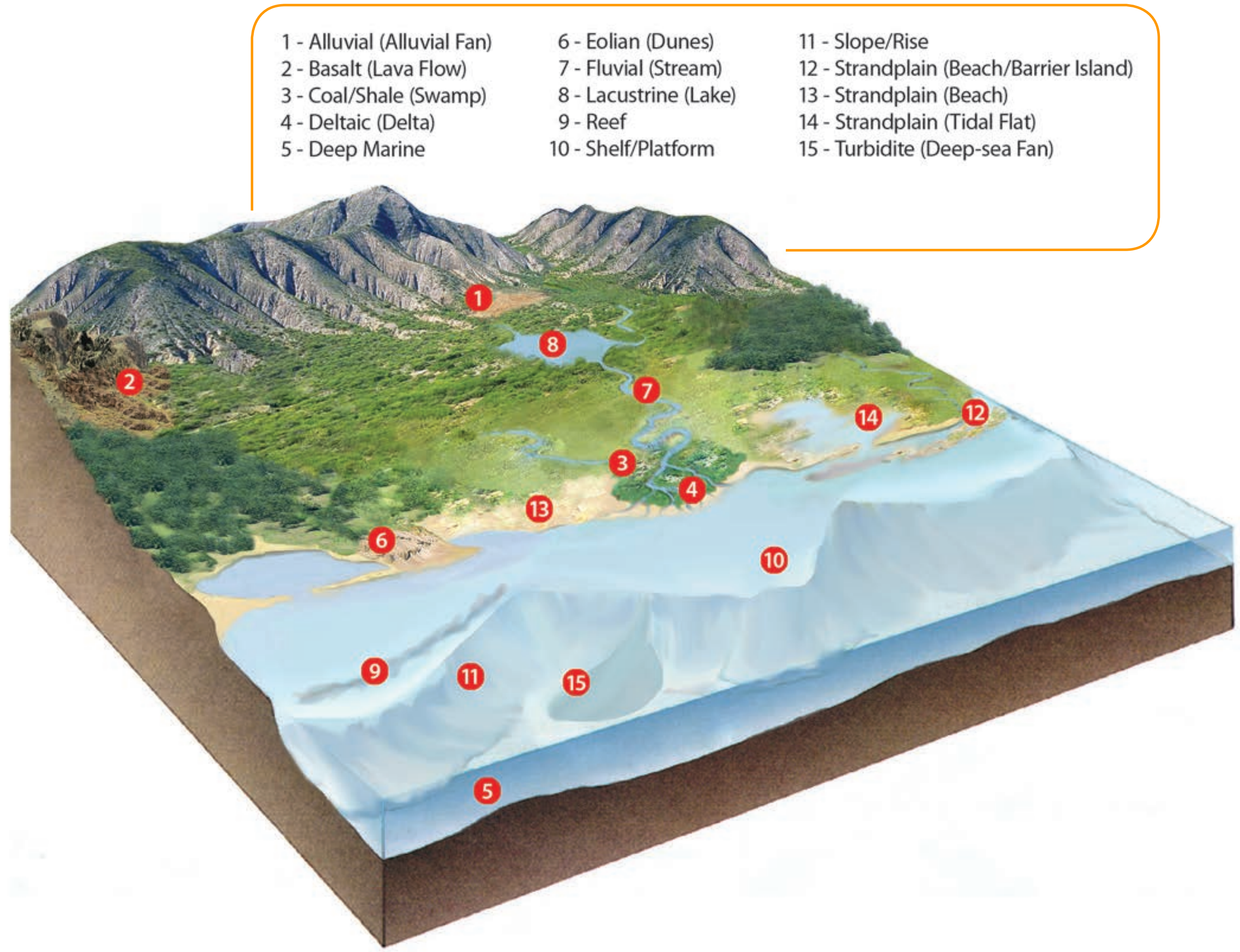
This map displays data that were obtained by the RCSPs and other sources and compiled by NATCARB. Canadian and Mexican data provided by Natural Resources Canada (NRCan) and the Mexican Ministry of Energy (SENER) can be found in the North American Carbon Storage Atlas, available at: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/NACSA2012.pdf. Carbon dioxide geologic storage information in NACAP was developed to provide a high-level overview of CO_2 geologic storage potential. Areal extents of geologic formations and CO_2 resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCS technologies can contribute to the reduction of CO_2 emissions and is not intended to serve as a substitute for site-specific assessment and testing. Please note that data resulting in a straight edge in the map above is indicative of an area lacking sufficient data and is subject to future investigation.

Geologic Storage Formation Classes

Identifying suitable geologic storage sites involves a methodical and careful analysis of both technical and non-technical aspects of potential sites. Each type of geologic formation has different opportunities and challenges. While geologic formations are infinitely variable in detail, geologists and engineers in the petroleum industry have classified formations by their trapping mechanism, hydrodynamic conditions, lithology, and, more recently, by depositional environment. The depositional environment, which is the area where 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 for long-term containment of liquids and gases, within individual storage reservoirs.

A primary goal of DOE's Carbon Storage Program is to classify the depositional environments of various formations known to have excellent reservoir properties that are amenable to geologic CO_2 storage. For fluid flow in porous media, knowledge of how depositional environments formed and directional tendencies imposed by the depositional environment can influence how fluid flows within these systems today and how CO_2 in geologic storage might flow in the future. Although post depositional processes may have degraded or modified the original depositional environment (by mineral deposition or dissolution), the basic stratigraphic framework created during deposition remains. Geologic processes working today are similar to when the sediments were initially deposited. Analysis of modern day depositional analogs, evaluation of core, outcrops, and well logs from subsurface formations provide insight to how these formations were deposited and how CO_2 is anticipated to migrate through the formation.

There are three types of rocks: metamorphic, igneous, and sedimentary. Metamorphic rocks are not currently being evaluated for CO_2 storage. While igneous rocks comprise 95 percent of the Earth's crust, the only igneous rocks currently being evaluated for CO_2 storage are basalts. Most basalts have high amounts of calcium, which can react with CO_2 to form a mineral, calcite, resulting in permanent CO_2 storage. Sedimentary rocks are the most promising type of rock being evaluated for CO_2 storage. There are three types of sedimentary rocks: (1) clastics, such as sandstone (broken fragments derived from preexisting rocks); (2) chemical precipitates, such as carbonates (limestone) and rock salt; and (3) organics (plant or animal constituents that may form coal or limestone). At this time, most geologic storage reservoirs are either clastics or carbonates (both precipitates and organic), where CO_2 is stored in the pore spaces between grains or fractures that are often filled with brine. In this type of CO_2 storage system impermeable layers are required to form a confining zone that prevents the upward migration of CO_2. For more information, see NETL's "Geologic Storage Formation Classifications: Understanding Its Importance and Impacts on CCS Opportunities in the United States," available at: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/BPM_GeologicStorageClassification.pdf.



		Matrix of Field Activities in Different Reservoir Classes (2012)										
		High Potential Reservoirs					Medium Potential Reservoirs				Lower/Unknown Potential Reservoirs*	
Large-Scale Field Projects[a]	Saline	-	-	1	1	-	1	-	1	-	-	-
	EOR	1	-	-	-	1	2	-	-	-	-	-
Small-Scale Field Projects[b]	Saline	2	1	1	1	-	-	-	1	-	-	1
	EOR	1	1	3	1	2	1	-	1	-	6	0
Reservoir Class		Deltaic	Shelf Clastic	Shelf Carbonate	Strandplain	Reef	Fluvial Deltaic	Eolian	Fluvial & Alluvial	Turbidite	Coal	Basalt (LIP)

Notes:

The number in the cell is the number of investigations by NETL per geologic storage formation classification.

* Potential reservoirs were inferred from petroleum industry and field data from the Carbon Storage Program.

[a] Large-Scale Field Projects – Injection of more than 1,000,000 tons of CO_2.

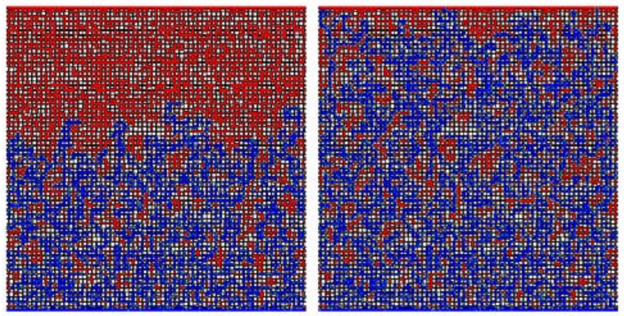
[b] Small-Scale Field Projects – Injection of less than 500,000 tons of CO_2 for EOR and 100,000 tons for saline formations.

Current DOE Methodology Research and Development for CCUS

NETL is actively engaged in research to better understand factors that control CO_2 storage in geologic formations and better characterize storage potential by developing and refining methodologies for CO_2 storage potential in saline, oil and gas, and unconventional formations. NETL's Office of Research and Development (ORD) provides DOE's Fossil Energy R&D Program with an onsite "corporate laboratory," where government engineers and scientists perform fundamental and applied fossil energy R&D. In addition, ORD offers a venue for participation in collaborative research, and it evaluates 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 programs managed under the Office of Coal and Power R&D. The Geological and Environmental Sciences Focus Area is the primary ORD focus area supporting the Carbon Storage Program.

Depleted Oil and Gas Fields

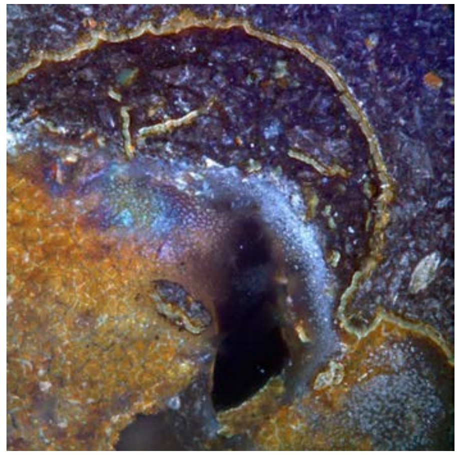
The current NETL methodology to assess CO_2 storage capacity in oil- and gas-bearing reservoirs includes two alternative approaches: volumetric and production-history-based techniques. NETL's ORD is reviewing the appropriateness and sufficiency of these methodologies, and developing a case study of CO_2 storage through RCSP that employs field and production data to evaluate volumetric, production-history-based, and alternative methodologies. Based on results of these efforts, NETL will propose refinements to ensure that the procedure is explicit and consistent with other NETL methodologies, including incorporation of uncertainties about reservoir properties and storage efficiency. Results of this evaluation will be published to benefit future resource assessments by RCSPs and other interested entities.



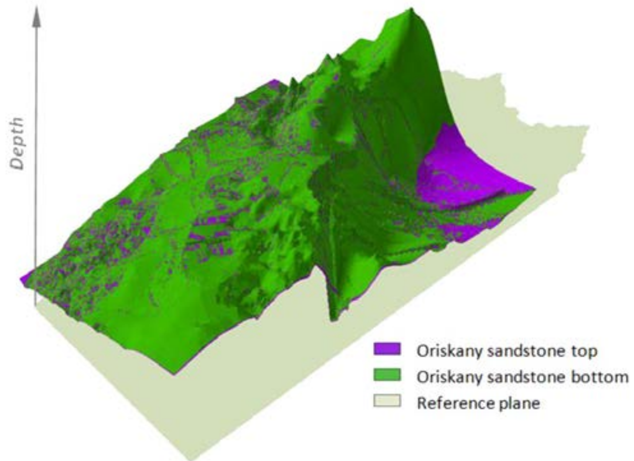
Microscopic displacement (E_d) efficiency is the fraction of the CO_2 contacted, water-filled pore volume that can be replaced by CO_2. This term is directly related to irreducible water saturation in the presence of CO_2. The microscopic displacement term identifies the fraction of pore space unavailable due to immobile in-situ fluids.

Saline Formations

NETL's ORD is conducting a comparative evaluation among six published CO_2 storage methodologies (see Appendix C) to evaluate the ability to predict CO_2 storage in saline formations and better understand uncertainty in underlying assessment models. Additionally, NETL is assessing storage potential in the Oriskany Formation in the Appalachian Basin; performing a global sensitivity analysis to identify key parameters, such as depth, temperature, pressure, porosity, and permeability, that most impact assessed CO_2 storage potential; and evaluating implications of applying more detailed spatial parameters in the development of CO_2 storage resource potential estimates. The results will help assess the impact of in situ heterogeneities on storage potential.



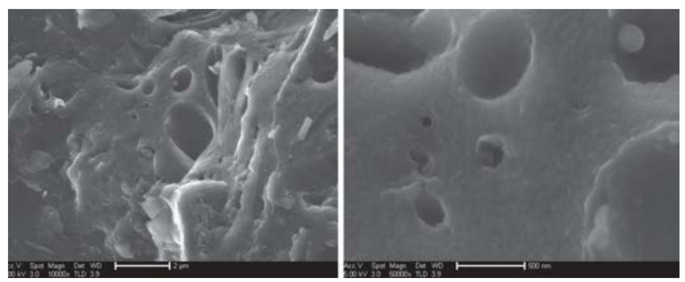
Brightfield photomicrograph of Columbia River Basalt vug filled with iron-hydroxide.



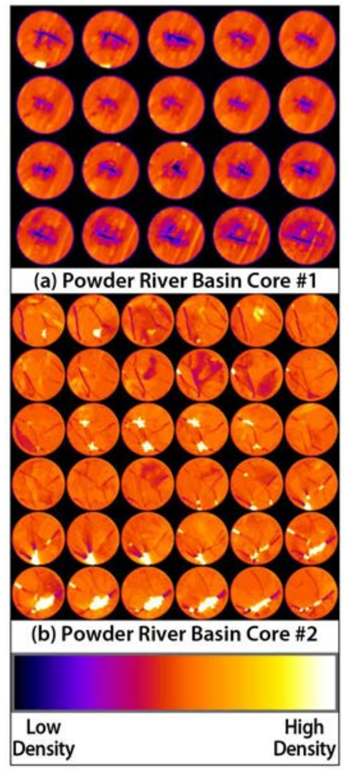
ArcGIS three-dimensional image for the Oriskany sandstone top and bottom. (Courtesy of Carnegie Mellon University through the NETL-RUA partnership)

Unconventional Formations

Storage resource estimates for unconventional CCUS reservoirs, such as gas shales, coal seams, and basalts, require alternative approaches to assess CO_2 storage potential that account for key differences in these geologic units. Storage assessments in unconventional systems must consider structural features such as fracture density and connectivity, CO_2 sorption, and mineral kinetics. NETL's ORD is developing a prescriptive methodology for CO_2 storage resource assessments in unconventional hydrocarbon resources and basalts for application in the future development of RCSP CO_2 storage resource assessments. Additionally, NETL is developing preliminary assessments of site-scale CO_2 flooding in model shale gas formations to evaluate potential injectivity and technical CO_2 storage assessments, and the potential for beneficial utilization of injected CO_2 for improved natural gas recovery.



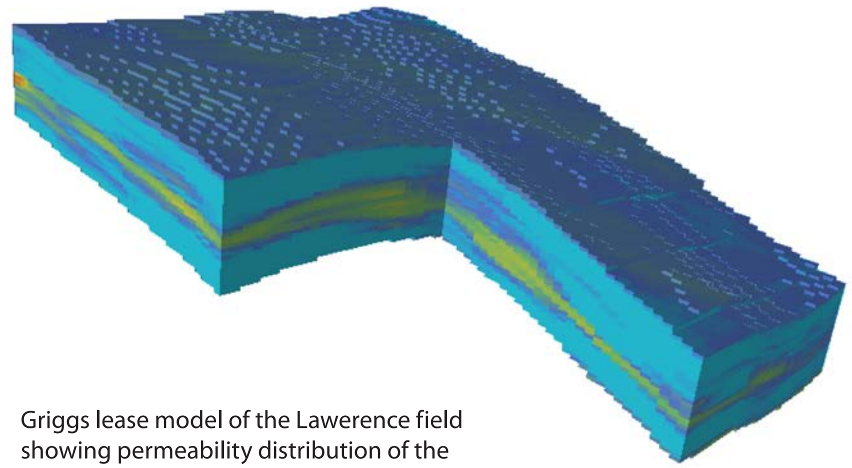
SEM images of the pore structure of coal.



Computed Tomography scans of Powder River coal under a 100 psi confining pressure.

An Improved Method to Estimate CO_2-EOR and Storage Resource

DOE is supporting the Midwest Geological Sequestration Consortium to integrate their experience and expertise to develop an improved general methodology for estimating CO_2-EOR and storage resource that is applicable to the RCSPs. The outcome will produce additional technical and economic screening criteria that can be applied to the Illinois Basin and compared to the Midwest Geological Sequestration Consortium's existing characterization effort.

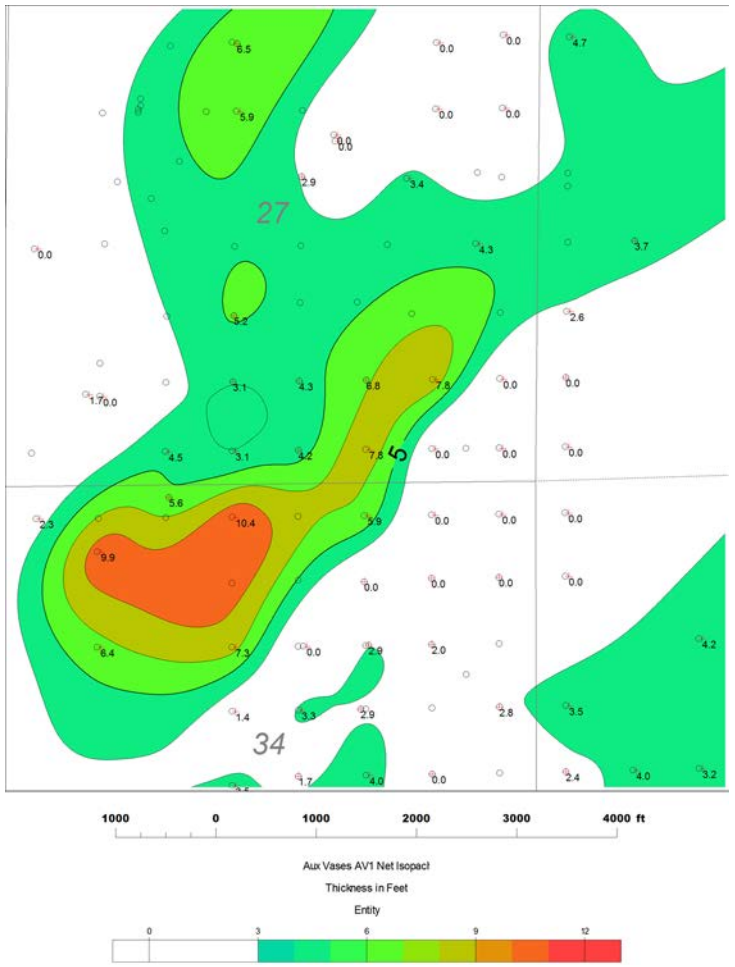


Griggs lease model of the Lawerence field showing permeability distribution of the field's flow units.

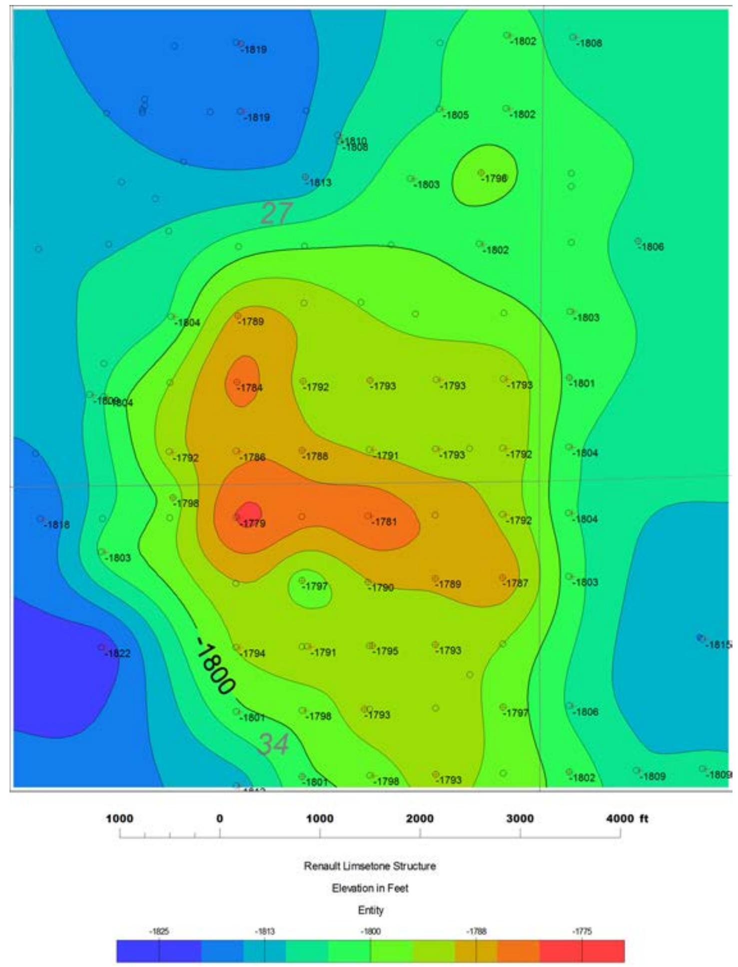
Advanced Resources International and the Midwest Geological Sequestration Consortium's proposed methodology seeks to develop and employ general CO_2-EOR performance type curves that reflect Illinois Basin geologic formation types in order to scope specific oilfields for CO_2-EOR potential. These performance curves will be tested against a rigorous geologic and reservoir model for calibration. In addition, a surface facility study is being conducted that includes capital and operating expenses, leading to the development of a baseline economic screening model.

The performance type curves are based on nine geologic models developed for the Midwest Geological Sequestration Consortium's Phase I oilfield assessment. Previous storage potential estimates used CO_2 oil recovery and storage efficiency factors in the volumetric calculations, which were based on the original oil in place. This current work seeks to improve the previous storage estimate methodology by utilizing oilfield performance (production) data to build an improved type curve tool similar to the Kinder-Morgan type curve model, which was based on West Texas CO_2 floods of Permian Basin carbonates. This new tool will build on existing data sets and models by incorporating new and updated oilfield specific data that will allow a history match of this model to specific field performance.

CO_2-EOR and storage will inevitably require capture and re-injection of produced CO_2 for low-pressure, low-temperature Illinois Basin oil reservoirs. The model will include field capital and operating expenses for capture, separation, and re-injection options that are appropriate for Illinois Basin oilfields. This information will be incorporated into a CO_2-EOR economic screening model to estimate the CO_2-EOR and storage resource using the performance type curves, which will be compared to current estimates using the methodology for select oilfields of the Illinois Basin that was developed during earlier characterization activities.



Aux Vases AV1 Net Isopact thickness map.



Elevation map of the Renault Limestone structure.

DOE's Current Systems Analysis Activities: NETL CO_2 Storage and Utilization Cost Models

NETL's Office of Program Planning and Analysis conducts analyses to demonstrate how R&D activities support national and international priorities related to energy supply, energy use, and environmental protection. This team also examines the following three areas of analysis (with respect to the Carbon Storage Program): (1) Systems—contextualizes research objectives (e.g., improvements in the cost and efficiency of CCUS technologies); (2) Policy—places CCUS in the context of regulatory compliance and environmental policy; and (3) Benefits—combines technology and policy to show economic and environmental costs and benefits that a successful carbon storage R&D program will provide both domestically and internationally. NETL has developed two CO_2 storage cost models: the FE/NETL Carbon Dioxide Transport and Storage (CTS)-Saline Cost Model and the FE/NETL CTS-EOR Cost Model.

The FE/NETL CTS–Saline Cost Model is a spreadsheet that estimates the revenues and capital, operating, and financial costs for a CO_2 storage project in a saline reservoir. These costs occur in one or more of the five stages of a storage project: regional geologic evaluation, site characterization, permitting, operations, and post-injection site care & site closure. The costs associated with long-term stewardship are not explicitly modeled. The model uses simplified reservoir engineering equations to model the storage process and includes a database of potential storage formations. The FE/NETL CTS-Saline Cost Model can estimate the revenue and costs for a single project or can cycle through the database of storage formations to generate the breakeven CO_2 price and CO_2 storage capacity for each storage formation. This data can be used to create a cost supply curve.

The FE/NETL CTS-EOR Cost Model is a spreadsheet that estimates the revenues and capital, operating and financial costs for a CO_2-EOR operation. It is based on the FE/NETL CTS-Saline Cost Model with modifications for modeling EOR operations. It uses NETL's CO_2 Prophet Model to simulate the inputs (water and CO_2) and outputs (oil, water, and CO_2) for a single pattern at a CO_2-EOR facility and incorporates a database of oil reservoirs developed by the EIA. The model includes the costs for complying with Subpart UU of the EPA's Greenhouse Gas Reporting Regulations. It also includes costs for complying with Subpart RR of the same regulations and the Underground Injection Control Program Class VI well regulations, should the user choose to include these costs. The FE/NETL CTS-EOR Cost Model can estimate the revenue and costs for performing CO_2-EOR at a single oil reservoir or cycle through the database of oil reservoirs to generate the break-even oil price and oil output for each oil reservoir. This data can be used to create a cost supply curve.

Stages of Operations for Geologic Storage and EOR Modeled in NETL's CO_2 Storage and Utilization Cost Models

	Regional Evaluation for a Specific Site	Site Selection & Characterization	Permitting	Operations	Post-Injection Monitoring	Long-Term Stewardship
Geologic Storage (GS) Class VI	**Negative Cash Flow**			**Positive Cash Flow Injection Fee**	**Negative Cash Flow**	**Trust Fund Covers Costs**
	• Volume of emissions to store & pore space needed. • Geologic, geophysical, engineering, financial & social. • Identify several prospective sites. Begin assembly of acreage block.	• Assemble/acquire new data. • Drill new well(s) & acquire seismic. • Get necessary permits. • Finish assembling acreage block. • Prepare required plans for Class VI permit. • Front-end engineering design for site. • Establish financial responsibility.	• Submit all plans and financial responsibility for permit application. • Approval to drill injection wells. State approves site permit. • Drill injection wells, incorporate new data in plans (AoR, etc) & present to Director. • Injection operations approved. • Have 180 days to submit monitoring, verification, and accounting plan per Subpart RR regs.	• Finish construction of surface facilities and MVA grid. • Begin injection of captured CO_2. • Follow plans, AoR every 5 yrs., annual reporting. • Annual mechanical integrity testing. • Drill new monitoring wells/perform corrective action as plume expands. • P&A injection wells per plan. • Some financial responsibility instruments released.	• Update & present post-injection site care & site closure plan to Director. • Apply for reduced time period. • Follow PISC & site closure plan. • Plugged and abandoned all wells, restore sites. • Release of financial responsibility instruments.	• Another entity accepts long-term stewardship, oversees trust fund, pays site costs, settles all claims.
	0.5 to 1 year	3+ years	2+ years	30 to 50 years	10 to 50+ years	Post Closure
Enhanced Oil Recovery (EOR) Class II	**Prospect Screening**	**Facility/Field Design**	**Facility/Field Construction**	**Operations**		
	Negative Cash Flow			**Positive Cash Flow Oil & Gas Sales**		
	• Technical and Economic Evaluation: 1. Reservoir & recoverable oil. 2. Facilities & costs.	• Wells, processing plant, pipelines, pattern development, etc. • Permitting, unitization. Contract for CO_2.	• Drill/workover wells, build plant, install pipelines, connect with CO_2 source, etc.	• Begin injection of CO_2. • Production of oil, gas, CO_2, and water gas processing, separation. • Recycling of CO_2. • O&M. • Closeout. • P&A wells at end.		
	1 to 2 years			20 to 50 years		

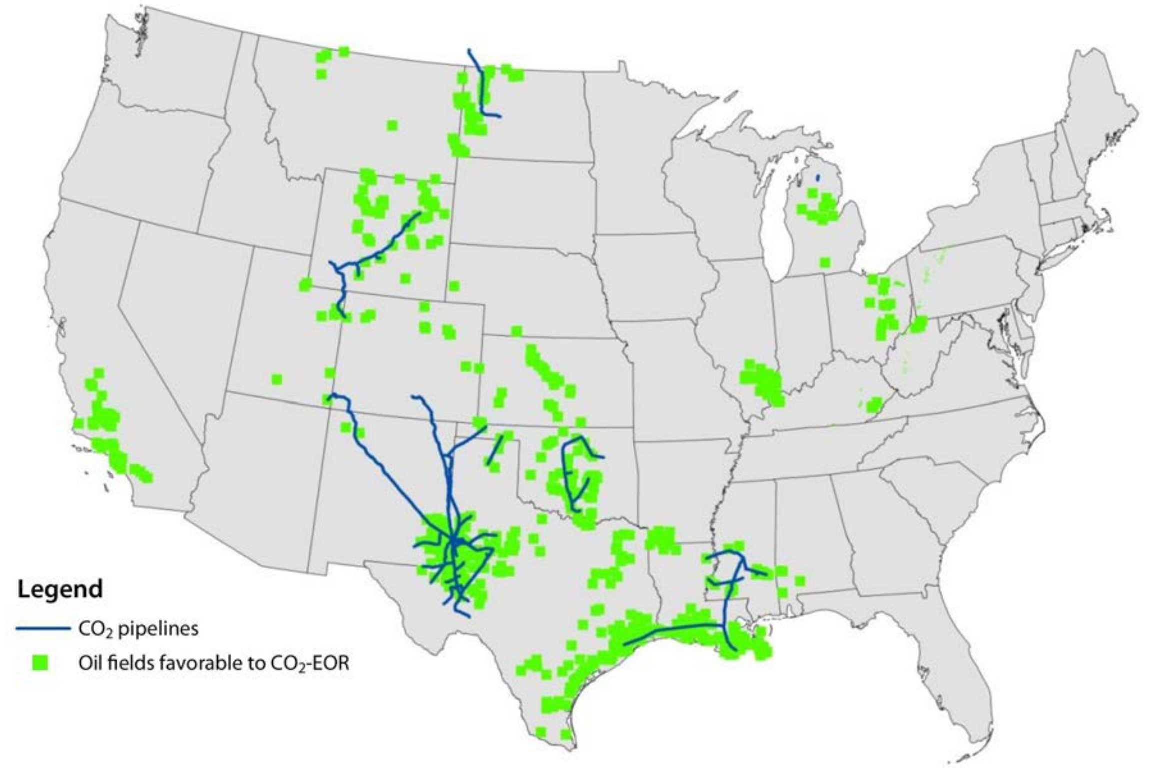
DOE's Current Systems Analysis Activities: CO_2-EOR Resource Assessment

Advanced Resources International has prepared an NETL-sponsored assessment of the amount of producible crude oil and the volume of CO_2 that can be stored by applying CO_2-EOR to oil-bearing formations underlying the United States. A proprietary database containing the oil properties and geologic characteristics of 1,800 onshore reservoirs and more than 4,000 offshore sands was used. The simulations for this assessment were conducted using the CO_2 Prophet Model, a screening tool that uses advanced computational techniques to model between injection wells and producing wells and estimates the magnitude and timing of oil production.

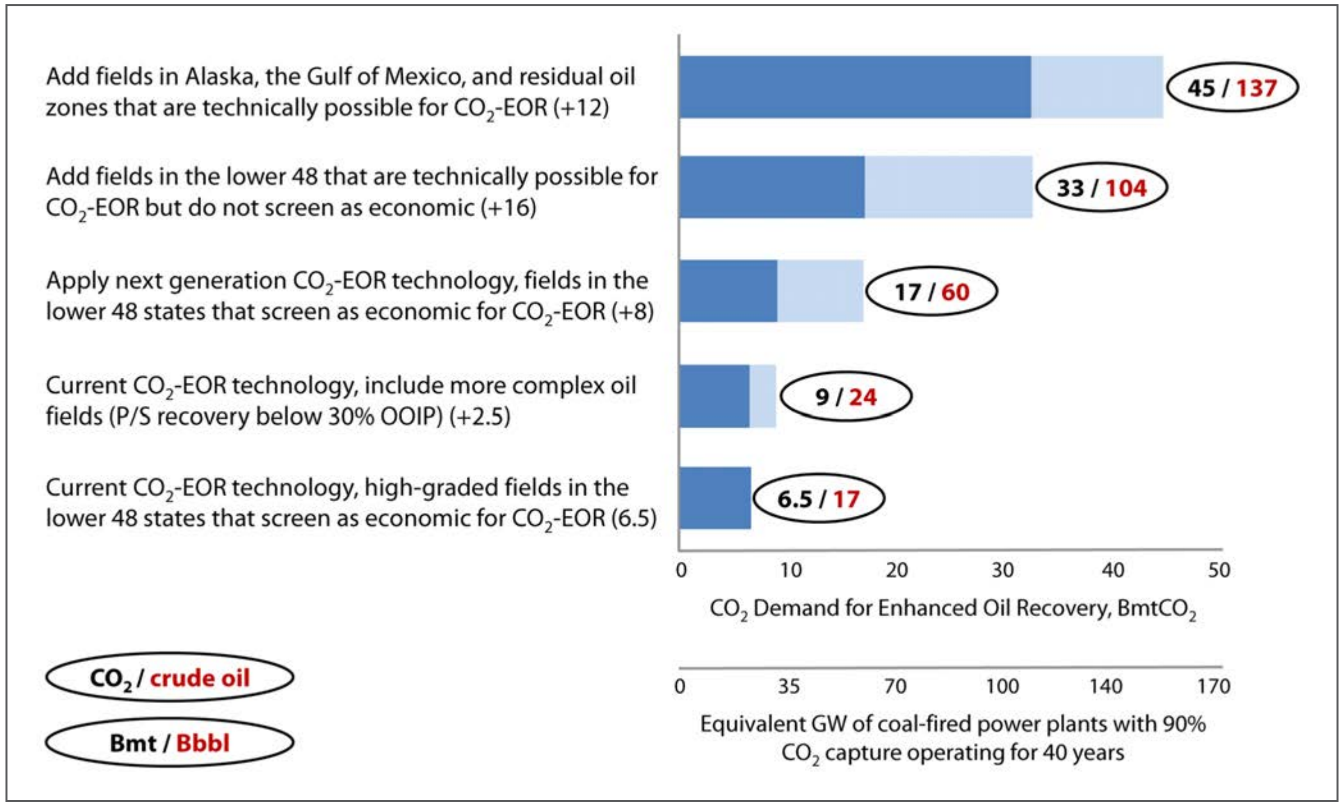
The figure to the right summarizes the results of this assessment. According to today's technology (based on CO_2 being available at $40/metric ton and the market price for crude oil sustained at $85/bbl), the continental United States holds an estimated 24 billion barrels of economically recoverable resource onshore. This level of crude oil production would demand and store approximately 9 billion metric tons of CO_2. Under a case with "next generation" CO_2-EOR technology, the economic resource number increases significantly to 60 billion barrels, and CO_2 demanded and stored increases to 17 billion metric tons. If one considers conventional oil-bearing formations where CO_2-EOR is technically possible but not economic (i.e., highly-fractured, low permeability, lower than minimum miscibility pressure, or other characteristics that make a CO_2 flood relatively difficult), the amount of crude oil production increases to 104 billion barrels and the CO_2 demand increases to 33 billion metric tons.

The estimated potential for CO_2-EOR can be increased further by including oil-bearing formations in Alaska, the offshore Gulf of Mexico, and residual oil zones. NETL is funding analyses to refine and improve the estimates for technical and economic resources for non-conventional CO_2-EOR settings.

The full report can be downloaded at http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=391.



Oil-bearing formations favorable for CO_2-EOR, onshore lower 48 states.
(Source: ARI disaggregated database, Ventex Velocity Suite Database)



NETL/ARI estimates for CO_2 storage capacity and crude oil production potential at oil-bearing formations in the United States. (Source: "Improving Domestic Energy Security and Lowering CO_2 Emissions with Next Generation CO_2 Enhanced Oil Recovery" (DOE/NETL 2011/150), June 2011.)

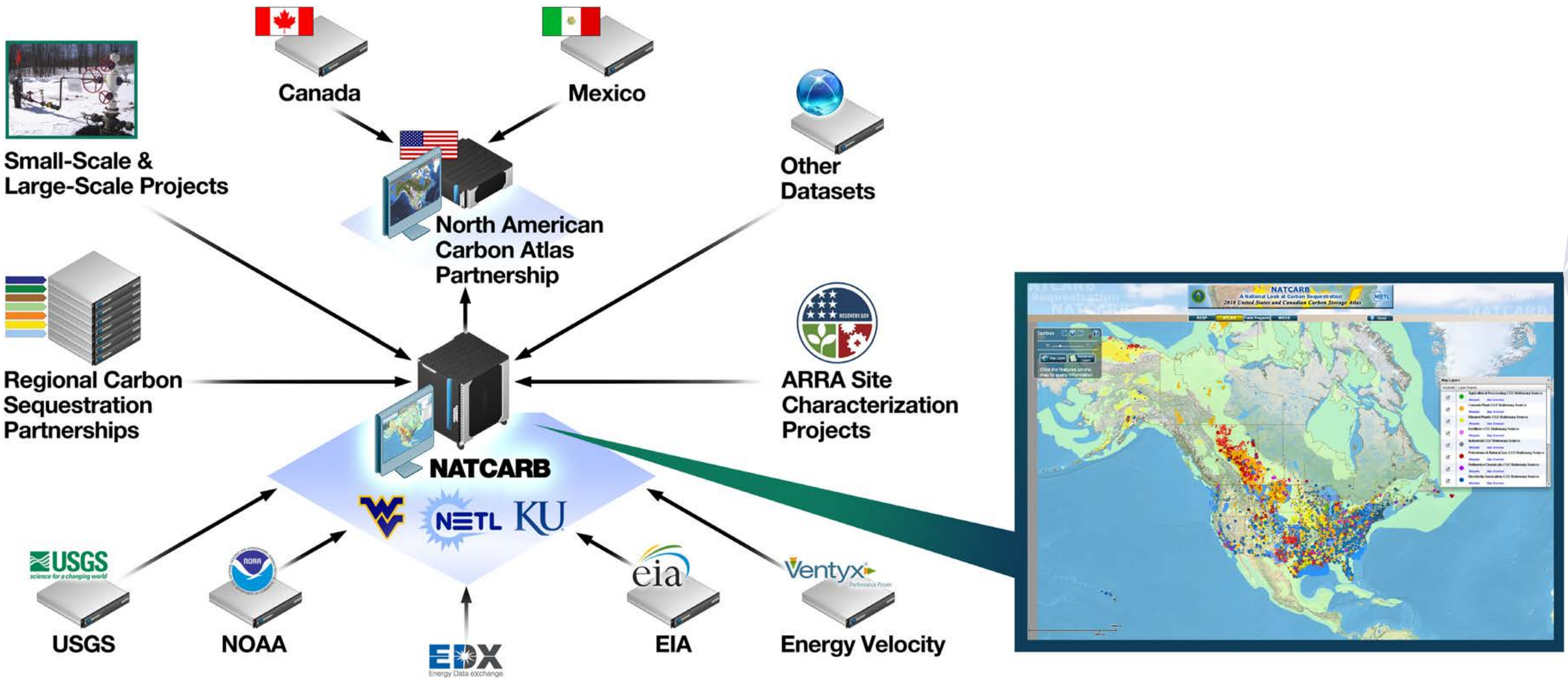
National Carbon Sequestration Database and Geographic Information System

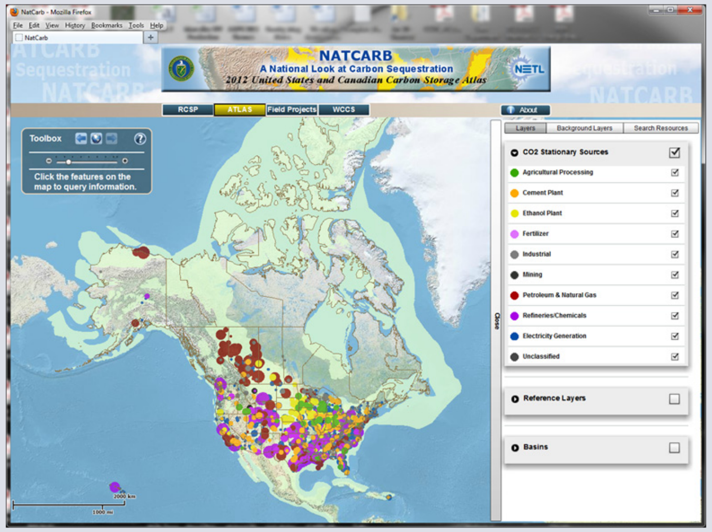
The National Carbon Sequestration Database and Geographic Information System (NATCARB) provides Web-based data access to disparate data and query and analytical tools required for addressing CCUS deployment. Data has been assembled from the RCSPs, the American Recovery and Reinvestment Act-funded site characterization projects, and other publicly accessible data repositories. NATCARB aims to construct a national carbon cyberinfrastructure, assembling the data required to address technical and policy challenges of CCUS.

NATCARB online access has been modified to better address the broad needs of all users. It includes not only geographic information system and database query tools for the high-end technical user, but also simplified displays for the general public, employing readily available Web tools.

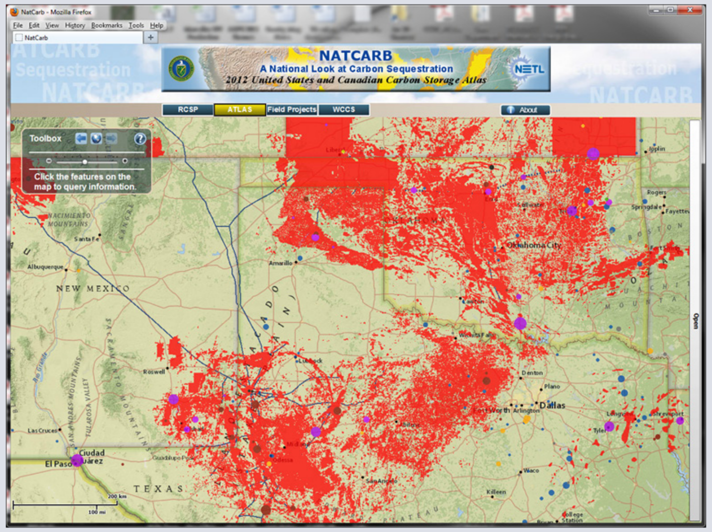
NATCARB organizes and enhances the critical information about CO_2 stationary sources and develops the technology needed to access, query and model, analyze, display, and distribute CO_2 storage resource data. Data are generated, maintained, and enhanced at each RCSP, or at specialized data warehouses and public servers (e.g., USGS-EROS Data Center, EPA, and ESRI). The information is assembled, accessed, and analyzed through a single geoportal.

All map layers and data tables used to construct the national estimates of CO_2 stationary sources and geologic storage resources are available for interactive display and download through the NATCARB website (http://www.netl.doe.gov/technologies/carbon_seq/natcarb/index.html).





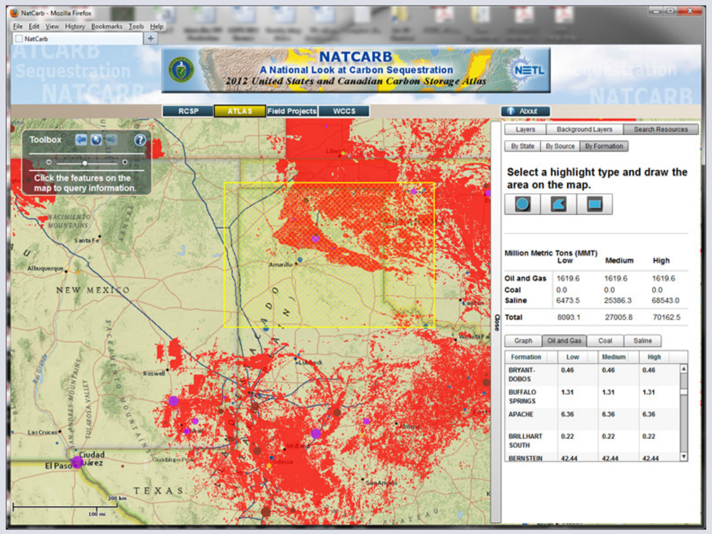
The NATCARB Viewer provides flexible tools for display and access to CCUS information covering the United States and parts of Canada. The display above shows sedimentary basins and large stationary CO_2 sources. Through the navigation panel on the right, the user can change the display elements, zoom to specific areas, and perform queries.



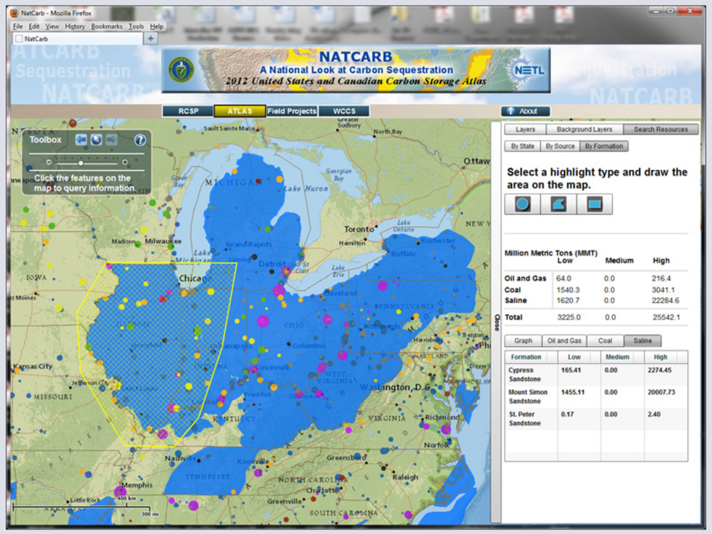
The NATCARB Viewer zoomed to the southern midcontinent of the United States, displaying oil and gas fields, CO_2 pipelines, and stationary sources. The navigation panel on the right has been minimized. The background has been changed to show major cities and highways.

The NATCARB Viewer

http://www.netl.doe.gov/technologies/carbon_seq/natcarb/index.html



The result of a query covering the northern panhandle of Texas. The image displays the potential CO_2 storage resources and a listing of the potential storage resource in individual oil and gas fields.



The result of a polygon query covering the Illinois Basin. The image displays the potential CO_2 storage resources and a listing of the potential storage resource in saline formations. Also displayed are large CO_2 stationary sources.

Energy Data eXchange™ (EDX)

In support of DOE's goals, NETL's Office of Research & Development created the Energy Data eXchange™ (EDX), an online research collaboration and coordination effort that provides access to research datasets from and for a wide variety of sources. Offering an innovative online research resource, EDX provides researchers, students, and policy makers a collaborative platform from which to work and access information and data relevant to fossil and renewable energy systems. EDX serves as a research and rapid response tool for a wide variety of users. Groups and individuals can search, download, and contribute datasets and information in a quick and easy-to-use environment, and EDX continues to evolve and grow with addition of customized tools that empower users to collaborate together in a uniform environment or work individually.

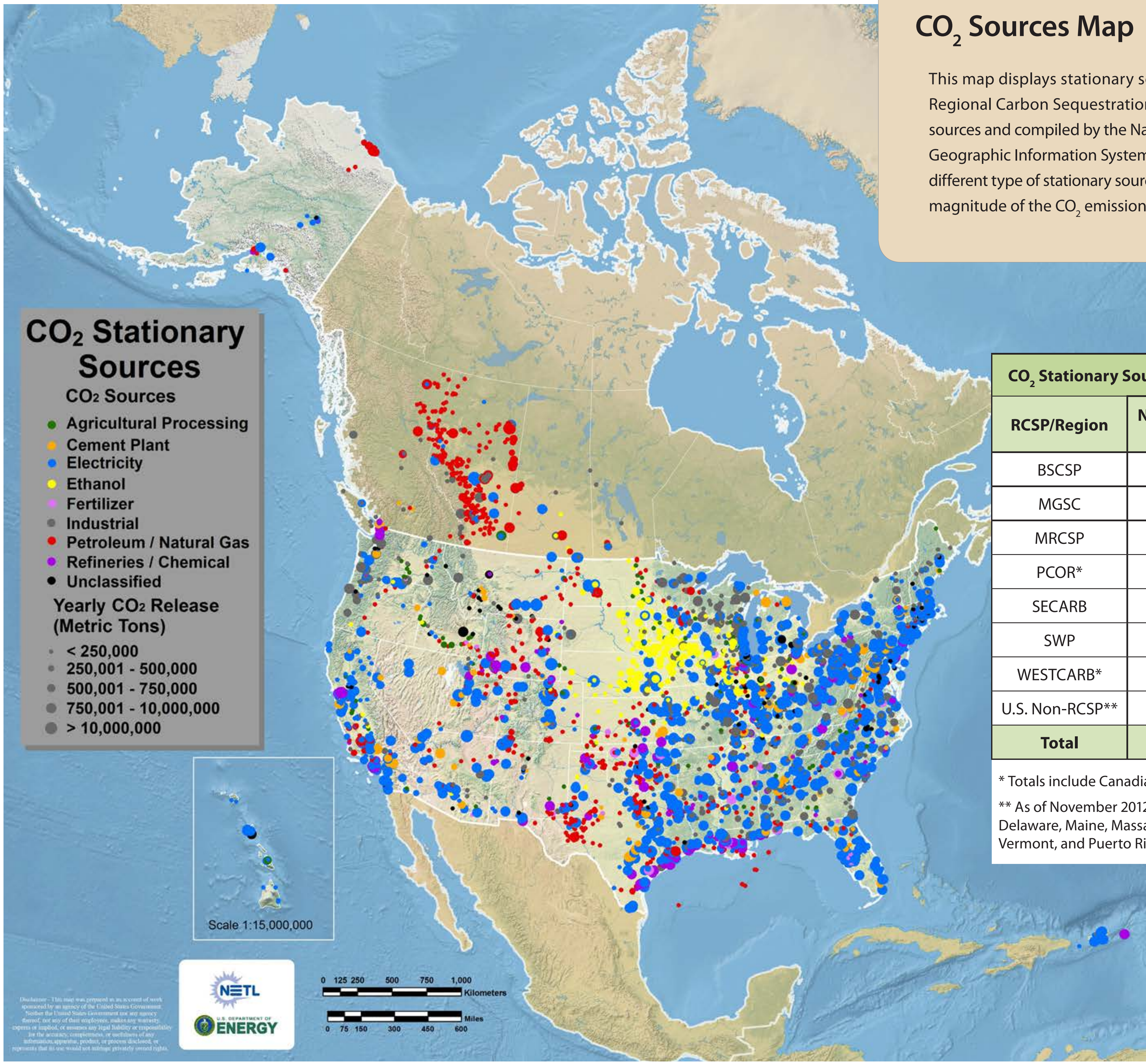
EDX Version 1 went live online July 27, 2012, and is now available at http://edx.netl.doe.gov. In addition to the data warehouse and portal, ongoing EDX efforts include development and maintenance of custom specialty tools and solutions to support online analysis and evaluation of key datasets for researchers and the public.

In addition, EDX was developed to facilitate the efficient delivery of the expansive collection of data and resources obtained over many years of publicly funded DOE fossil energy research programs, such as structured datasets including NATCARB, as well as other unstructured CO_2 storage datasets beyond NATCARB. In addition, research areas such as CCUS may benefit from data and resources coordinated through EDX that were originally collected for other purposes (such as hydrocarbon development) and now find alternate uses from a new research community and initiative.

National Perspectives

CO_2 Sources Map

This map displays stationary source data that were obtained from the Regional Carbon Sequestration Partnerships (RCSPs) and other external sources and compiled by the National Carbon Sequestration Database and Geographic Information System (NATCARB). Each colored dot represents a different type of stationary source with the dot size representing the relative magnitude of the CO_2 emission source (see map legend).



CO_2 Stationary Source Emission Estimates by RCSP/Region		
RCSP/Region	**Number of Sources**	**CO_2 Emissions (million metric tons per year)**
BSCSP	244	48
MGSC	311	291
MRCSP	443	670
PCOR*	926	517
SECARB	1,003	1,103
SWP	649	333
WESTCARB*	513	268
U.S. Non-RCSP**	156	49
Total	**4,245**	**3,279**

* Totals include Canadian sources identified by the RCSP.

** As of November 2012, "U.S. Non-RCSP" includes Connecticut, Delaware, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, and Puerto Rico.

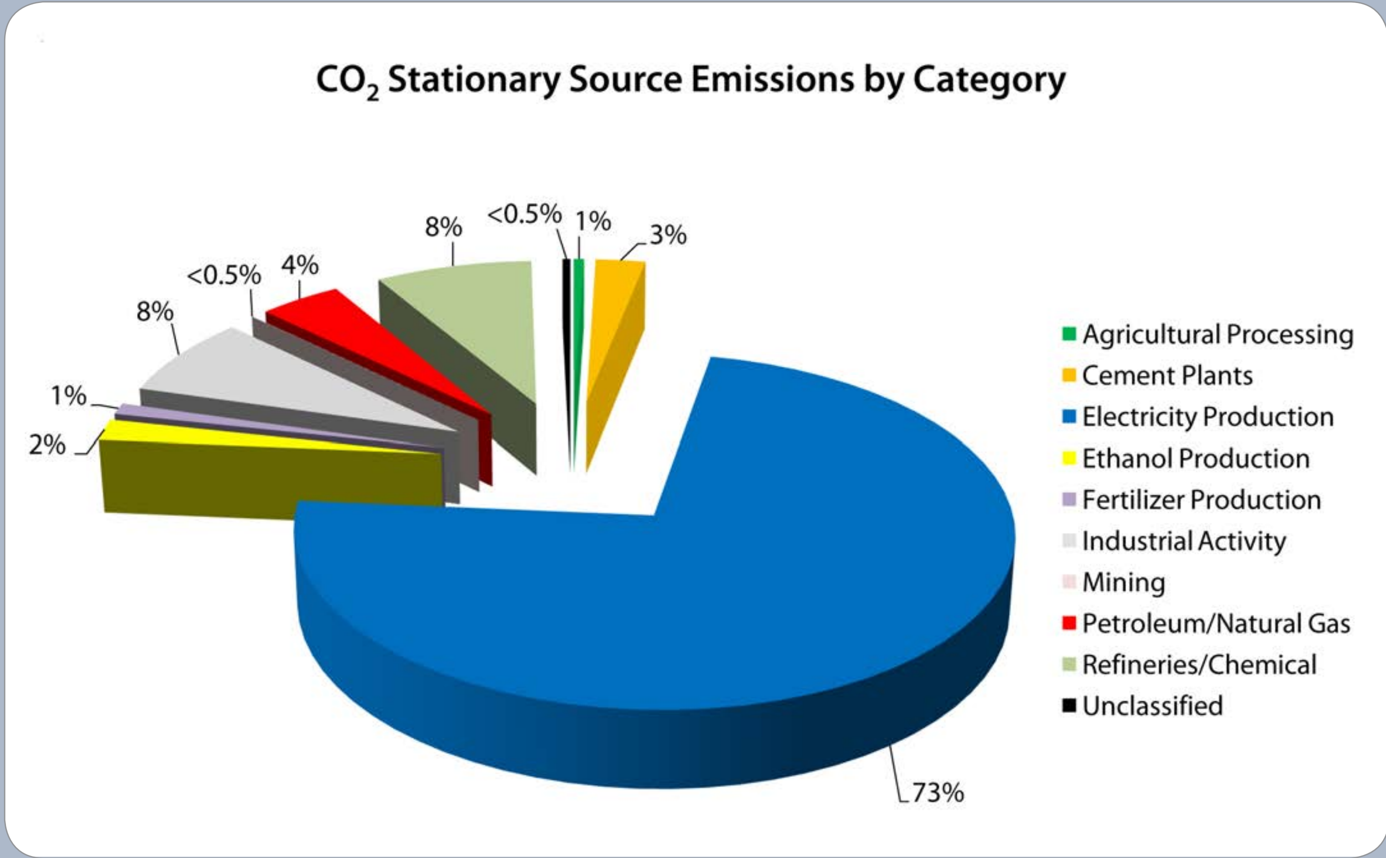
CO_2 Sources

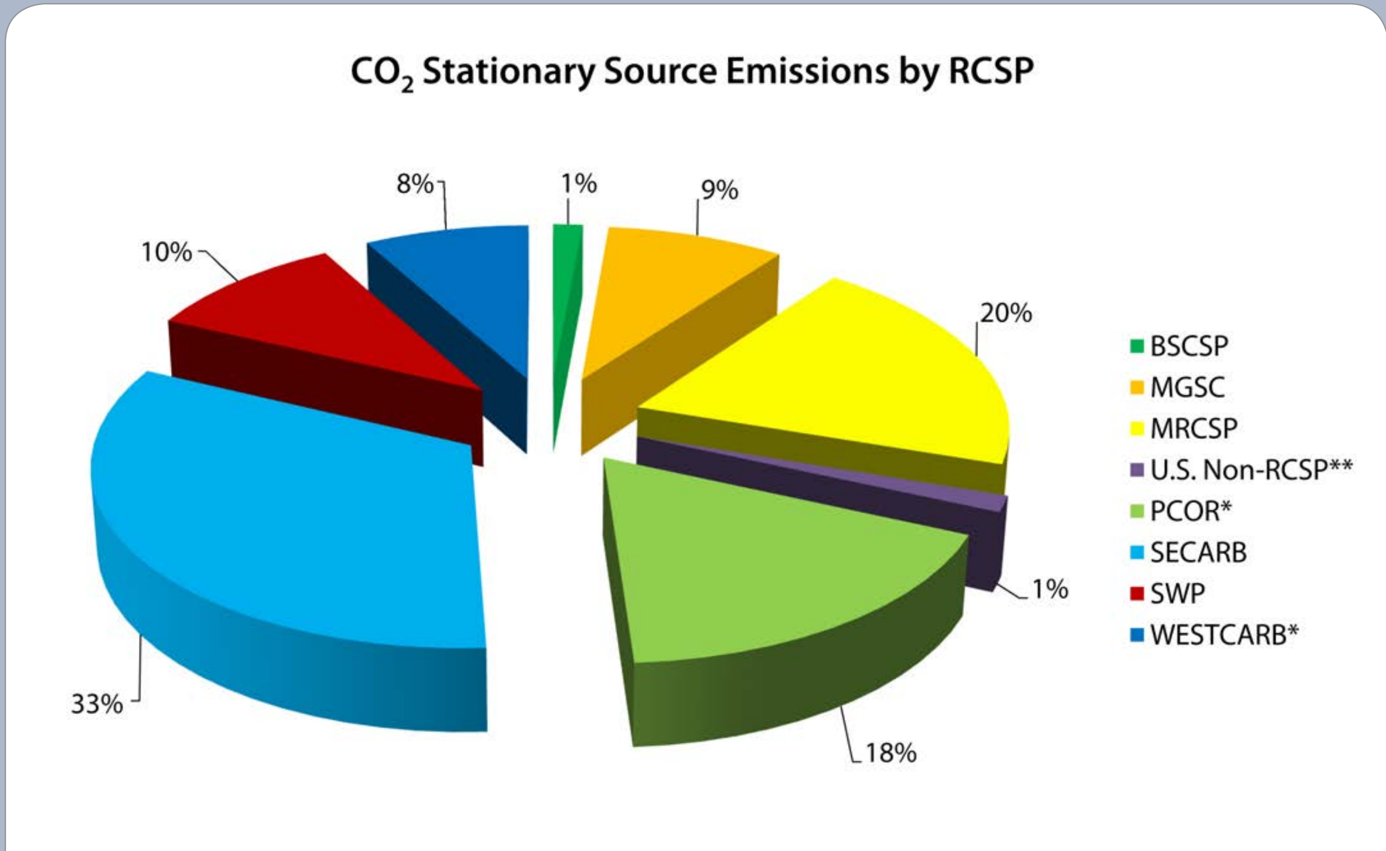
There are two different types of CO_2 sources: natural and anthropogenic (manmade). Natural sources include respiration from animals and plants, volcanic eruptions, forest and grass natural fires, decomposition of biomass material (plants and trees), and naturally occurring sources in geologic formations. Anthropogenic sources result from human activity and include the burning of fossil fuels, cement production and other industrial processes, deforestation, agriculture, and changes in natural land usage. Although CO_2 emissions from natural sources are estimated to be greater than the anthropogenic sources, natural sources are usually in equilibrium with a process known as the global carbon cycle, which involves carbon exchange between the land, ocean, and atmosphere. Increases in anthropogenic emissions throughout the last 200 years have led to an overall increase in the concentration of CO_2 and other greenhouse gases in the atmosphere.

In the United States, DOE's RCSPs have documented the location of 4,245 large stationary CO_2 sources (each emitting more than 100,000 metric tons per year) with total annual emissions of approximately 3,279 million metric tons of CO_2.

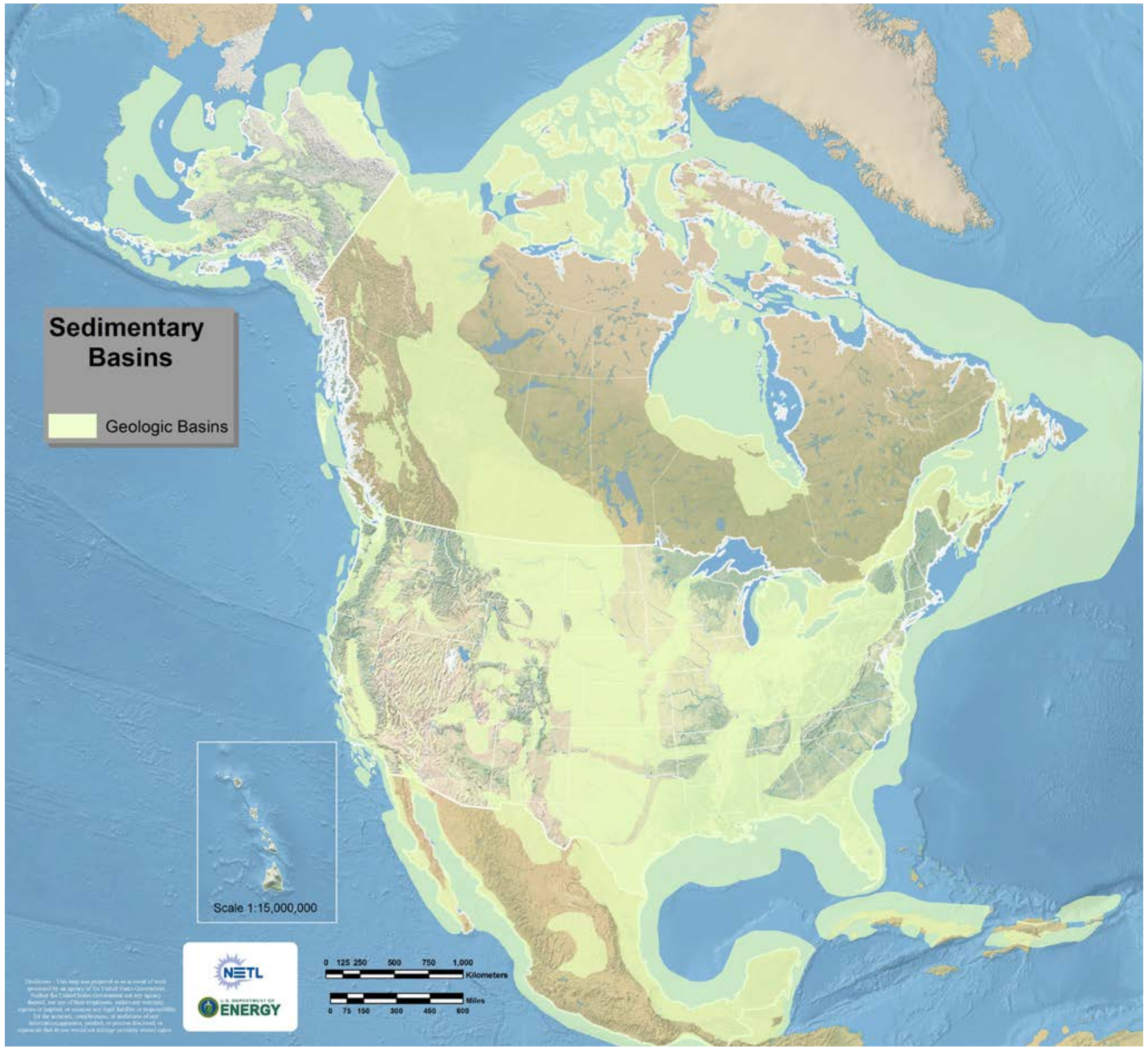
For details on large stationary sources of CO_2 by state, see Appendix D. For more information on the methodologies used to estimate these emissions, please see Appendix A. More detailed information on regional sources can be found in the RCSP section of this Atlas and information on Canadian and Mexican source data can be found in the North American Carbon Storage Atlas at www.nacsap.org.

The number of sources and emissions reported in this Atlas was based on information gathered by the RCSPs and NATCARB as of May 2012.





* Includes only Canadian Sources Identified by RCSP
** As of November 2012, "U.S. Non-RCSP" includes Connecticut, Delaware, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, and Puerto Rico



Sedimentary Basins

The Regional Carbon Sequestration Partnerships have identified and examined the location of potential CO_2 injection formations in different sedimentary basins throughout the United States and Canada. These sedimentary basins collected sediments that lithified to become sedimentary rocks. If these sedimentary rocks are porous or fractured, they can be saturated with brine (water with a high total dissolved solids concentration), oil, or gas. If the sedimentary rock is permeable (e.g., many sandstones), it could be a target for CO_2 injection. If it is impermeable (e.g., many shales), it could act as a confining zone to prevent migration of CO_2. Necessary conditions for a CO_2 storage site are the presence of both a reservoir with sufficient injectivity and a seal to prevent migration.

Brine is water that contains appreciable amounts of salts that have either been leached from the surrounding rocks or from seawater that was trapped when the rock was formed. The U.S. Environmental Protection Agency (EPA) has determined that a saline formation used for CO_2 storage must have at least 10,000 parts per million of total dissolved solids—a measure of the amount of salt in water. Most drinking water supply wells contain a few hundred parts per million or less of total dissolved solids.

Oil and gas reservoirs are often saline formations that have traps and seals that allowed oil and gas to accumulate over millions of years. Many oil and gas fields contain stacked formations (different reservoirs over top of each other), which have characteristics, including good porosity, that make for excellent multiple target locations at one geologic storage site.

Supercritical (Dense Phase) CO_2

It is common for experts to talk about storing CO_2 in the supercritical (dense phase) condition. In supercritical condition, CO_2 is at a temperature in excess of 31.1 °C and a pressure in excess of 72.9 atm (about 1,057 psi); this temperature and pressure defines the critical point for CO_2. At such temperatures and pressures, the CO_2 has some properties like a gas and some properties like a liquid. In particular, it is dense like a liquid but has viscosity like a gas. The main advantage of storing CO_2 in the supercritical condition is that the required storage volume is substantially less than if the CO_2 were at standard (room) pressure conditions. This reduction in volume is illustrated in the figure at right. The blue numbers show the volume of CO_2 at each depth compared to a volume of 100 at the surface.

Temperature naturally increases with depth in the Earth's crust, as does the pressure of the fluids (brine, oil, or gas) in the rocks. At depths below about 800 meters (about 2,600 feet), in most places on Earth, the natural temperature and fluid pressures are in excess of the critical point of CO_2. This means that CO_2 injected at these temperatures and pressures will be in the supercritical condition. The pressure of CO_2 must be greater than the naturally existing fluid pressure in order to inject the CO_2 into the reservoir. Large temperature differences between the injected CO_2 and the surrounding rock are not recommended; however, the CO_2 will take on the temperature of the surrounding rock as it moves into the reservoir. Hence, even if not injected under supercritical conditions, it will—in most cases—end up in the supercritical condition in the reservoir.

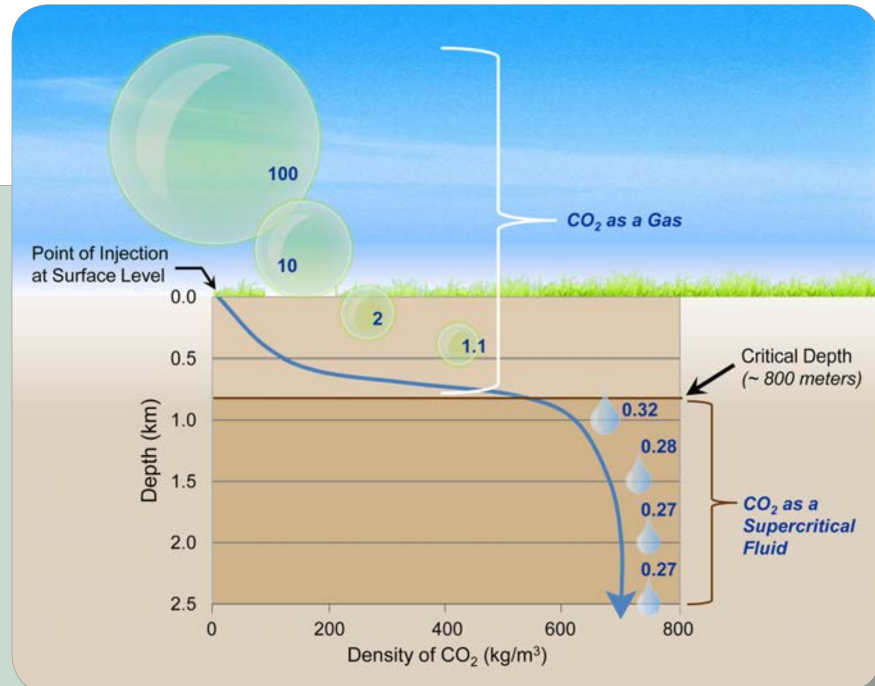


Illustration of pressure effects on CO_2 volume (based upon image from the Cooperative Research Centre for Greenhouse Gas Technologies [CO2CRC]).

Oil and Gas Reservoirs

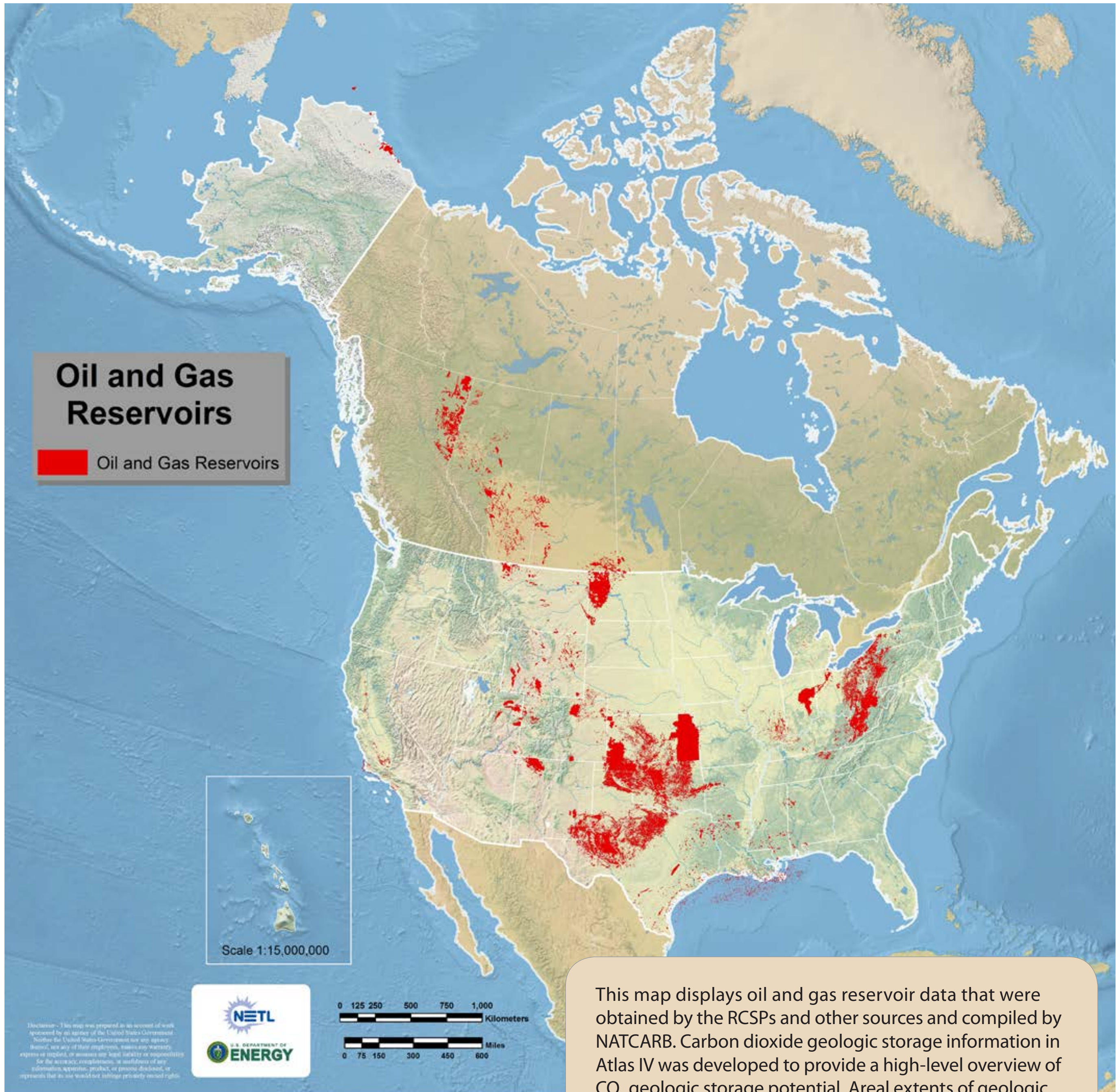
Oil and gas reservoirs are porous rock formations (usually sandstones or carbonates) containing hydrocarbons (crude oil and/or natural gas) that have been physically trapped. There are two main types of physical traps: (1) stratigraphic traps, created when changes have occurred in rock types, and (2) structural traps, in which the rocks have been folded or faulted to create a trapping reservoir. Oil and gas reservoirs are ideal geologic storage sites because they have held hydrocarbons for thousands to millions of years and have conditions suitable for CO_2 storage. Furthermore, their architecture and properties are well known as a result of exploration for and production of these hydrocarbons. In addition, due to the industrialization of these sites, infrastructure exists for CO_2 transportation and storage.

Traditionally, oil can be extracted from a reservoir in three different phases. The primary recovery phase uses the natural pressure in a reservoir to push the oil up. This process usually accounts for 10 to 15 percent of oil recovery. The secondary recovery phase involves the injection of water to increase the reservoir pressure and displace the oil towards producing wells. This process produces an additional 15 to 25 percent of the original oil. Together, these two phases account for the recovery of 25 to 40 percent of the original oil, but approximately two-thirds of the oil remains in the reservoir. Tertiary recovery, or enhanced oil recovery (EOR), is frequently conducted with CO_2 to recover additional original oil. When CO_2 is injected, it raises the reservoir pressure and increases the oil mobility, making it easier for the oil to reach producing wells. This method, called CO_2-EOR, is an attractive option for CO_2 storage because it allows for the recovery and sale of additional oil that would otherwise remain trapped in the reservoir, thus lowering the net cost of CO_2 storage. In North America, CO_2 has been injected into oil reservoirs to increase oil recovery for more than 40 years.

While not all potential mature oil and gas reservoirs in the United States have been examined, DOE's RCSPs have documented the location of approximately 225 billion metric tons of CO_2 storage resource. For details on oil and gas reservoir CO_2 storage resource by state/province, see Appendix D. For more information on the methodologies used to estimate this potential, please see Appendix B. More detailed regional oil and gas reservoir storage information can be found in the RCSP section of this Atlas, and information on Canadian oil and gas storage data can be found in the North American Carbon Storage Atlas at www.nacsap.org.

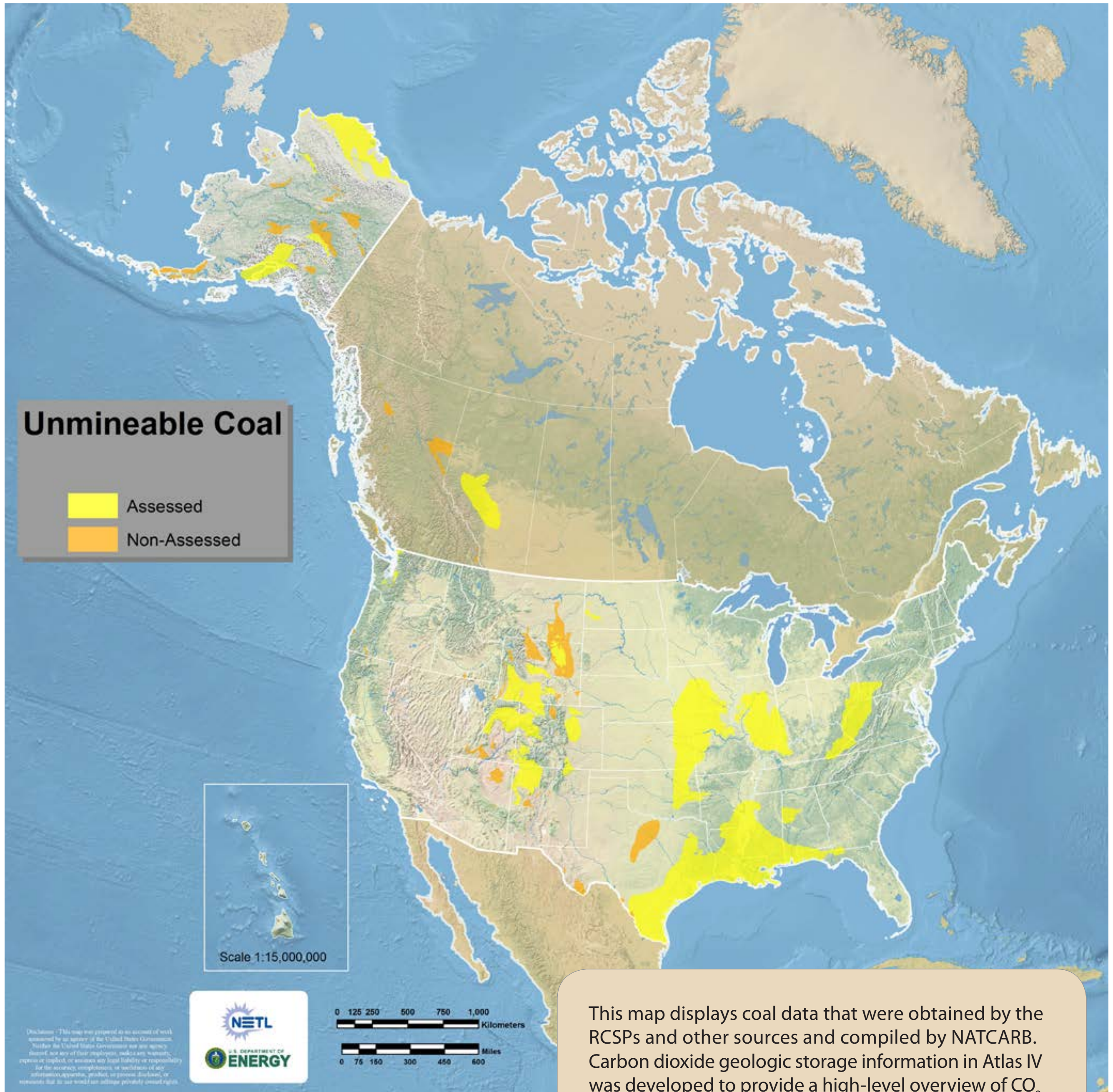
The storage resource estimates reported in this Atlas were based on information gathered by the RCSPs and NATCARB as of November 2012.

CO_2 Storage Resource Estimates for Oil and Gas Reservoirs by RCSP		
RCSP	**Billion Metric Tons**	**Billion Tons**
BSCSP	1	1
MGSC	1	1
MRCSP	14	15
PCOR	25	28
SECARB	32	35
SWP	149	164
WESTCARB	4	4
Total	**226**	**248**



This map displays oil and gas reservoir data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas IV was developed to provide a high-level overview of CO_2 geologic storage potential. Areal extents of geologic formations and CO_2 resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCUS technologies can contribute to the reduction of CO_2 emissions and is not intended to serve as a substitute for site-specific assessment and testing. Please note that oil and gas reservoir data resulting in a straight edge in the map above is indicative of an area lacking sufficient data and is subject to future investigation.

EOR operations in Michigan. (Courtesy of MRCSP)



This map displays coal data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas IV was developed to provide a high-level overview of CO_2 geologic storage potential. Areal extents of geologic formations and CO_2 resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides carbon capture, utilization, and storage (CCUS) project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCUS technologies can contribute to the reduction of CO_2 emissions and is not intended to serve as a substitute for site-specific assessment and testing. Please note that coal data resulting in a straight edge in the map above is indicative of an area lacking sufficient data and is subject to future investigation.

Skyland coalbed in Kentucky. (Courtesy of MRCSP)

Unmineable Coal

Coal that is considered unmineable because of geologic, technological, and economic factors (typically too deep, too thin, or lacking the internal continuity to be economically mined with today's technologies) may have potential for CO_2 storage. Coal preferentially adsorbs CO_2 over methane, which is naturally found in coal seams, at a ratio of 2 to 13 times. This property, known as adsorption trapping, is the basis for CO_2 storage in coal seams. Methane gas is typically recovered from coal seams by dewatering and depressurization, but this can leave significant amounts of methane trapped in the seam. The process of injecting and storing CO_2 in unmineable coal seams to enhance methane recovery is called enhanced coalbed methane (ECBM) recovery. Enhanced coalbed methane recovery parallels CO_2-EOR because it provides an economic benefit from the recovery and sale of the methane gas, which helps to offset the cost of CO_2 storage. However, for CO_2 to be stored in coals, the coal must have sufficient permeability, which controls injectivity. Coal permeability depends on the effective stress and usually decreases with increasing depth. Furthermore, studies have shown that CO_2 injection can impact coal permeability and injectivity.

For CO_2 storage in coals or ECBM recovery, the ideal coal seam must have sufficient permeability and be considered unmineable. Carbon dioxide need not be in the supercritical (dense phase) state for it to be adsorbed by coal, so CO_2 storage in coals can take place at shallower depths (at least 200 meters deep) than storage in oil and gas reservoirs and saline formations (which require at least 800 meters depth). Research to optimize CO_2 storage in coals is ongoing.

While not all unmineable coal has been examined, DOE's RCSPs have documented the location of approximately 56 to 114 billion metric tons of potential CO_2 storage resource in unmineable coal. For details on unmineable CO_2 storage resource by state, see Appendix D. For more information on the methodologies used to estimate this potential, please see Appendix B. More detailed regional coal storage information can be found in the RCSP section of this Atlas. Information on Canadian and Mexican coal storage data can be found in the North American Carbon Storage Atlas at www.nacsap.org.

The storage resource estimates reported in this Atlas were based on information gathered by the RCSPs and NATCARB as of May 2012.

CO_2 Storage Resource Estimates for Coal by RCSP				
RCSP	Low		High	
	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	1	1	1	1
MGSC	2	2	3	3
MRCSP	1	1	1	1
PCOR	7	8	7	8
SECARB	33	36	75	83
SWP	1	1	2	2
WESTCARB	11	12	25	28
Total	**56**	**61**	**114**	**126**

Saline Formations

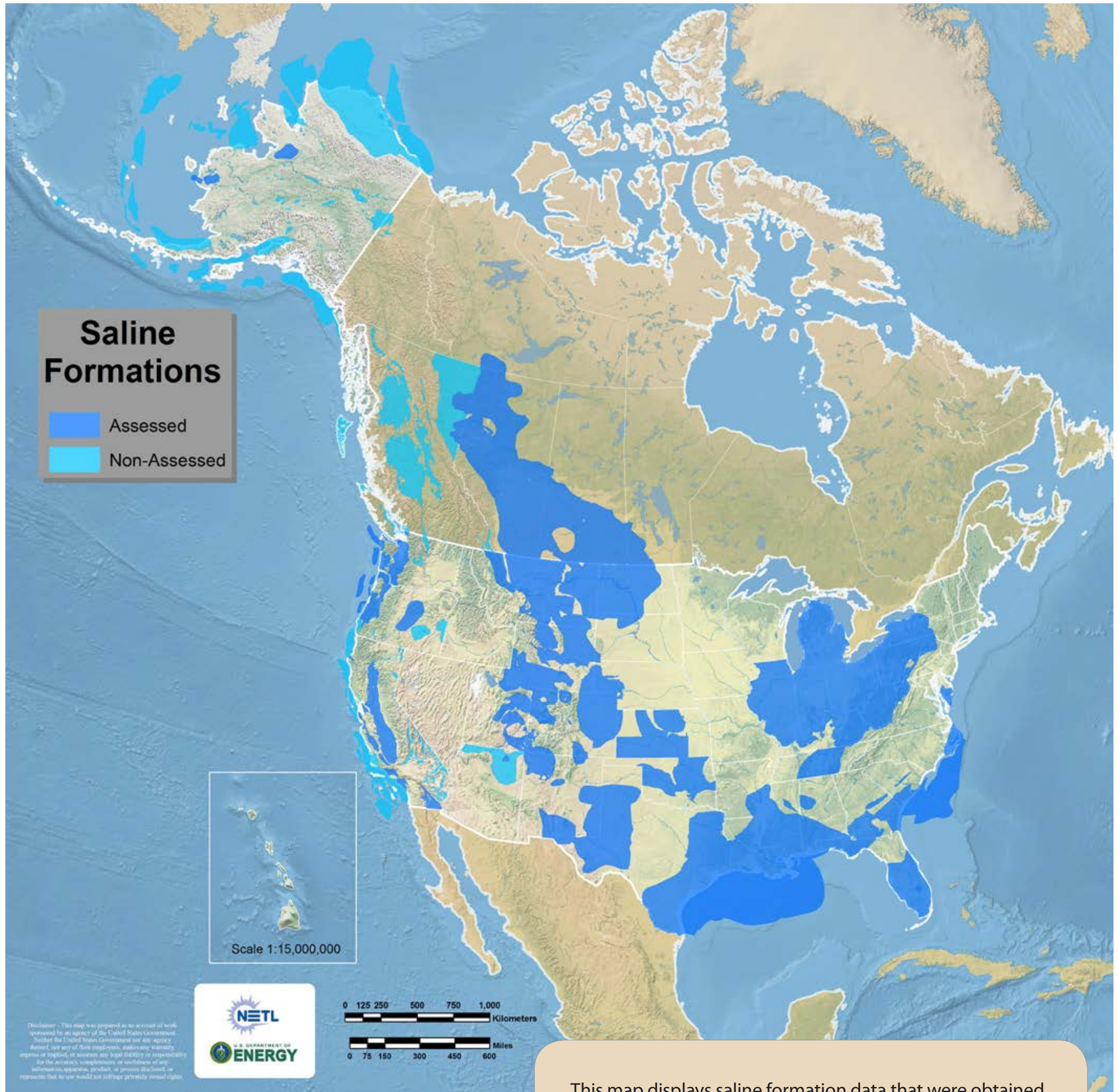
Saline formations are layers of sedimentary porous and permeable rocks saturated with salty water called brine. These formations are fairly widespread throughout North America, occurring in both onshore and offshore sedimentary basins, and they have potential for CO_2 storage. It is important that a regionally extensive confining zone (often referred to as caprock or seal) overlies the porous rock layer. Trapping mechanisms include the CO_2 dissolving in the brine (solubility trapping), reacting chemically with the minerals and fluid to form solid carbonates (mineral trapping), or becoming trapped in the pore space (volumetric trapping).

Saline formations are estimated to have much larger storage potential for CO_2 than oil and gas reservoirs and unmineable coals because they are more extensive and widespread. Much knowledge about some saline formations exists from the exploration and production of oil and gas, and prior oil industry experience, but there are also saline formations about which less is known. Although saline formations have a greater amount of uncertainty than oil and gas reservoirs, they represent an enormous potential for CO_2 storage, and recent project results suggest that they can be used as reliable, long-term storage sites. Saline formation storage lacks the economic incentives of CCUS storage in oil and gas reservoirs or unmineable coal areas; however, they represent a significant future storage resource and can serve as buffer storage for EOR operations.

While not all saline formations in the United States have been examined, DOE's RCSPs have documented an estimated CO_2 storage resource ranging from approximately 2,102 billion metric tons to more than 20,043 billion metric tons of CO_2. For details on saline formation CO_2 storage resource by state, see Appendix D. For more information on the methodologies used to estimate this potential, please see Appendix B. More detailed regional saline formation storage can be found in the RCSP section of this Atlas, and information on Canadian and Mexican saline storage data can be found in the North American Carbon Storage Atlas at www.nacsap.org.

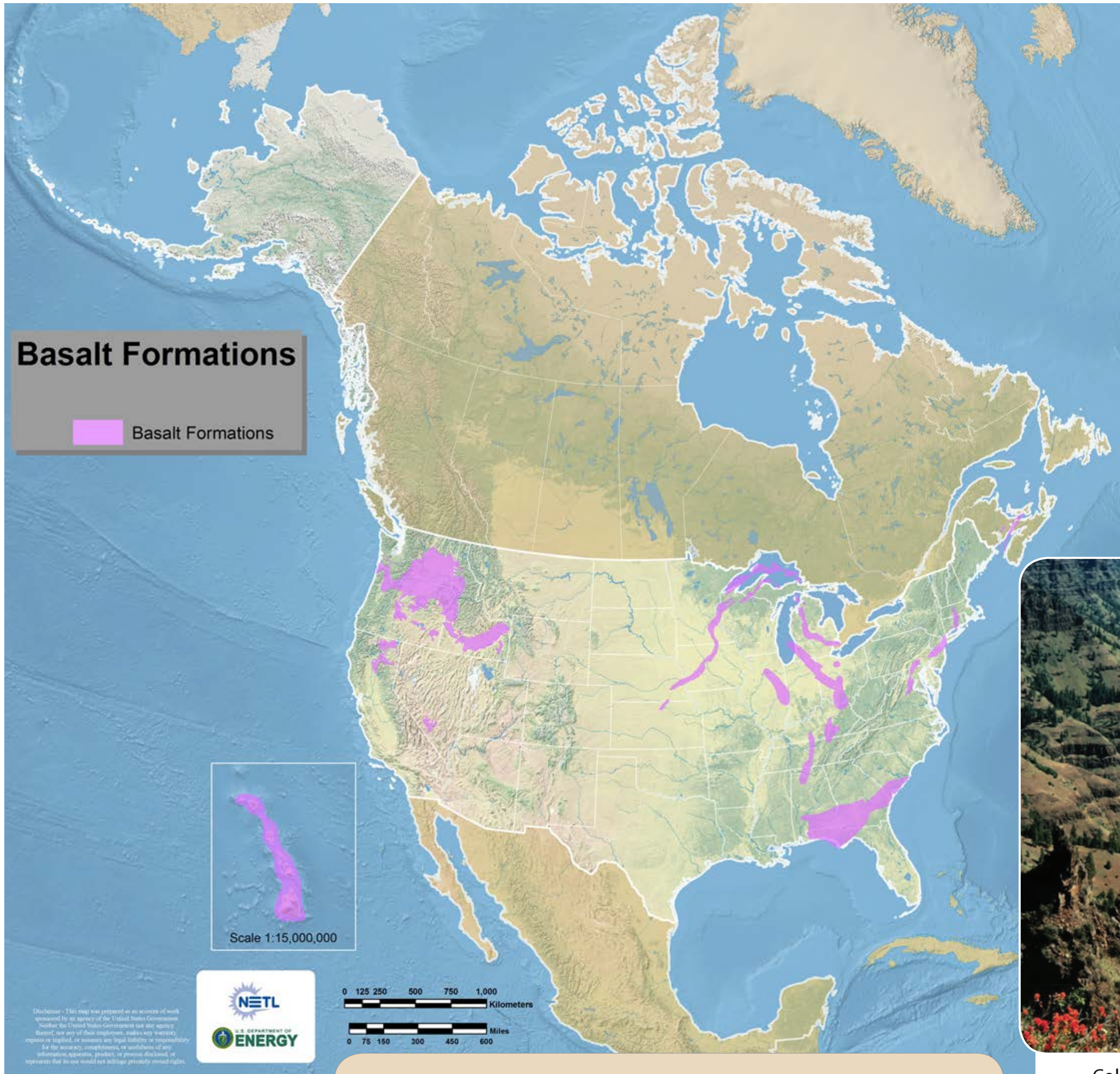
The storage resource estimates reported in this Atlas were based on information gathered by the RCSPs and NATCARB as of May 2012.

CO_2 Storage Resource Estimates for Saline Formations by RCSP				
RCSP	Low		High	
	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	98	108	1,237	1,364
MGSC	11	12	158	174
MRCSP	95	105	123	136
PCOR	174	192	511	563
SECARB	1,376	1,516	14,089	15,530
SWP	266	293	2,801	3,088
WESTCARB	82	90	1,124	1,239
Total	**2,102**	**2,316**	**20,043**	**22,094**



This map displays saline formation data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas IV was developed to provide a high-level overview of CO_2 geologic storage potential. Areal extents of geologic formations and CO_2 resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCUS technologies can contribute to the reduction of CO_2 emissions and is not intended to serve as a substitute for site-specific assessment and testing. Please note that saline formation data resulting in a straight edge in the map above is indicative of an area lacking sufficient data and is subject to future investigation.

Surface outcropping of a saline storage formation near Belfry, Montana. (Courtesy of John Talbott, BSCSP)



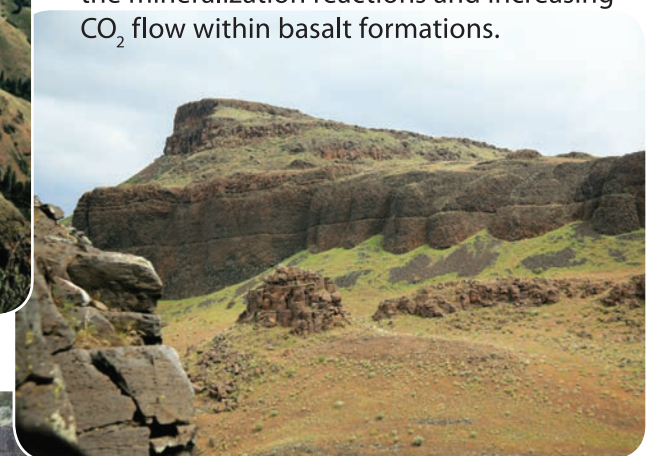
This map displays basalt formation data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas IV was developed to provide a high-level overview of CO_2 geologic storage potential. Areal extents of geologic formations presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCUS technologies can contribute to the reduction of CO_2 emissions and is not intended to serve as a substitute for site-specific assessment and testing. Carbon dioxide storage in basalt formations is an area of current research. Before basalt formations can be considered viable storage targets, a number of questions relating to the basic geology, the CO_2 trapping mechanisms and their kinetics, and monitoring and modeling tools need to be addressed. As such, *Atlas IV* presents a map of these potential future storage opportunities, but provides no CO_2 storage resource values for basalt formations.

Basalt Formations

Another potential CO_2 storage option DOE is investigating are geologic formations of solidified lava called basalt formations. The relatively large amount of potential storage resource in basalts, along with their geographic distribution, make them an important formation type for possible CO_2 storage, particularly in the Pacific Northwest and the southeastern United States. These formations have a unique chemical makeup that could potentially convert all of the injected CO_2 to a solid mineral form, thus isolating it permanently from the atmosphere.

The chemistry of basalts potentially allows injected CO_2 to react with magnesium and calcium in the rocks to form the stable carbonate mineral forms of calcite and dolomite. This mineralization process shows promise to be a valuable tool for carbon capture and storage (CCS) since the mineralization process permanently locks carbon in the solid mineral structure. Thus, basalts may offer one of the safest options for long-term isolation of CO_2 from the atmosphere because of the unique capacity for permanent incorporation of injected CO_2 into carbonates via mineralization. However, more research is needed to understand the time frames and actual chemical inputs and outputs of a basalt CO_2 injection. Some key factors affecting the capacity and injectivity of CO_2 into basalt formations are effective porosity of flow, top layers, and interconnectivity. DOE's current efforts are focused on enhancing and utilizing the mineralization reactions and increasing CO_2 flow within basalt formations.

Columbia River Basalt.



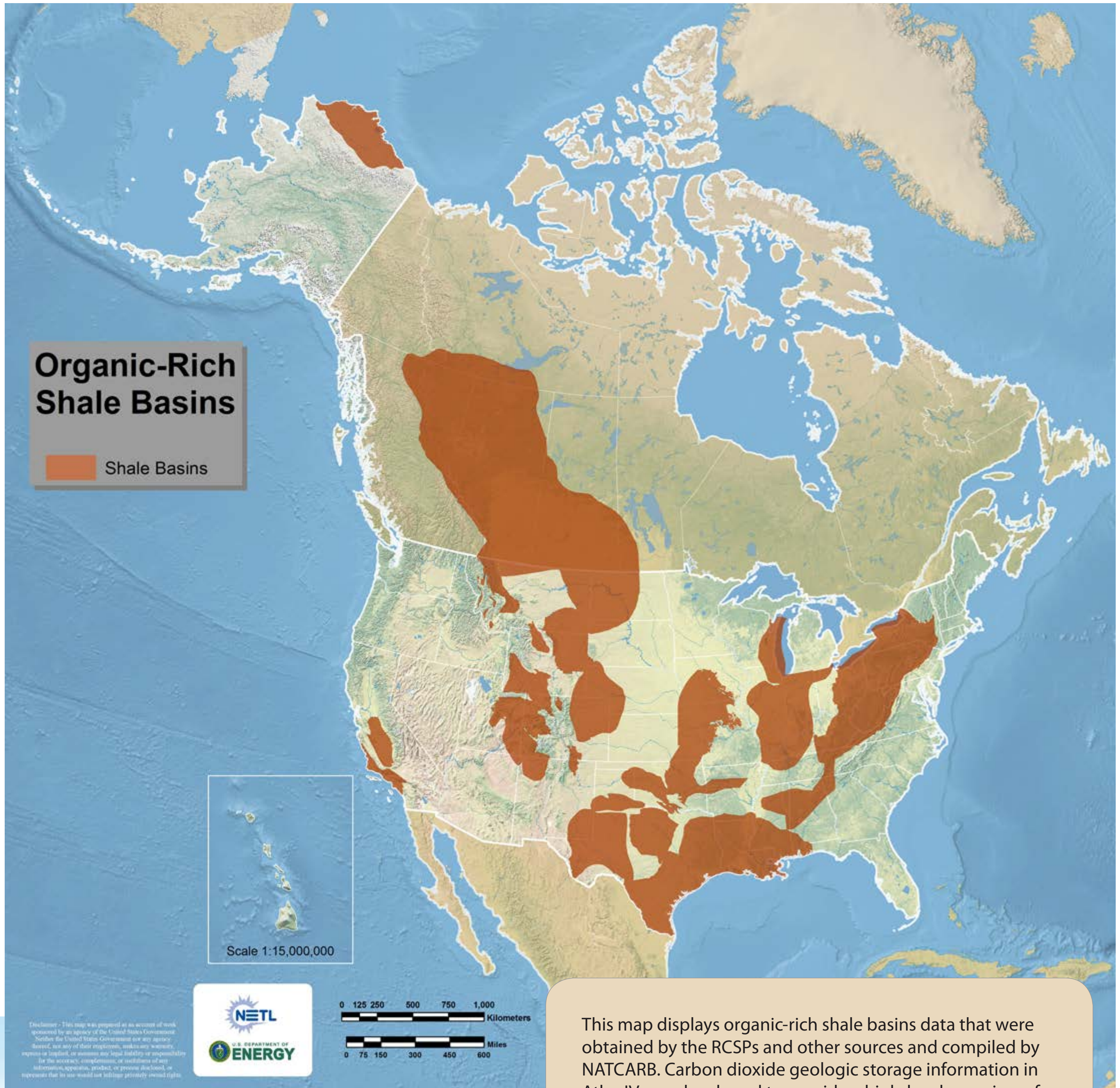
Basalt outcrop in eastern Washington. (Courtesy of Sarah Koenigsberg)

An example of a basalt flow. (Courtesy of Travia McLing, INL)

Organic-Rich Shale Basins

Organic-rich shales are another geologic storage option. Shales are formed from silicate minerals, which are degraded into clay particles that accumulate over millions of years. The plate-like structure of these clay particles causes them to accumulate in a flat manner, resulting in vertical rock layers with extremely low permeability. Therefore, shales are most often used in geologic storage as a confining zone or caprock.

Ongoing efforts are focused on using CO_2 for enhanced gas recovery. Through engineering, the horizontal permeability in shales can be preferentially increased, which makes CO_2 storage feasible. Recent technological advances in horizontal drilling and hydraulic fracturing have increased interest in the energy sector for natural gas production from organic-rich shales. With horizontal drilling and hydraulic fracturing, operators engineer porosity and permeability into organic-rich shales to create flow pathways. These technologies, coupled with the fact that CO_2 is preferentially adsorbed over methane, will improve the feasibility of using CO_2 for enhanced gas recovery (EGR) in much the same way as ECBM recovery. While the additional engineering of the rocks would add to the cost, the potential for hydrocarbon production could potentially offset it.



Geologist examining the base of the Marcellus Shale at an outcrop near Bedford, PA.

New Albany Shale outcrop. (Courtesy of MGSC)

This map displays organic-rich shale basins data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas IV was developed to provide a high-level overview of CO_2 geologic storage potential. Areal extents of geologic formations presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCUS technologies can contribute to the reduction of CO_2 emissions and is not intended to serve as a substitute for site-specific assessment and testing. Carbon dioxide storage in organic-rich shale basins is an area of current research. Before organic-rich shale basins can be considered viable storage targets, a number of questions relating to the basic geology, the CO_2 trapping mechanisms and their kinetics, and monitoring and modeling tools need to be addressed. As such, *Atlas IV* presents a map of these potential future storage opportunities, but provides no CO_2 storage resource values for organic-rich shale basins.

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REPORT NUMBER: DOE/NETL-2012/1589

Regional Carbon Sequestration Partnerships' Perspectives

Information contained in the following Regional Carbon Sequestration Partnerships' (RCSP) Perspectives Section was obtained from each RCSP. This information was collected and analyzed as part of the efforts of the RCSPs, and is not intended to be a comprehensive assessment of carbon capture, utilization, and storage (CCUS).

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

Big Sky Carbon Sequestration Partnership

The Big Sky Carbon Sequestration Partnership (BSCSP) is part of Montana State University's Energy Research Institute. BSCSP is developing safe, effective, and economical approaches for capturing and permanently storing CO_2 to reduce the region's greenhouse gas emissions. BSCSP employs existing technologies from the fields of engineering, geology, chemistry, biology, geographic information systems, and economics to develop novel approaches for both geologic and terrestrial carbon storage in the BSCSP region. BSCSP also engages in regulatory analyses, public education and outreach, and innovative research to evaluate the merits of new technologies.

The BSCSP region encompasses Montana, Wyoming, Idaho, South Dakota, and eastern Washington and Oregon. BSCSP represents a coalition of organizations, including universities, national laboratories, private companies, state agencies, and international collaborators. BSCSP partners are engaged in many aspects of research and operations, ranging from project permitting to regional storage potential characterization to geologic reservoir modeling.

The characterization of potential formations confirms that the BSCSP region holds an abundance of potential carbon storage sites. Saline formations are prevalent east of the Rocky Mountains and capable of storing several billion tons of CO_2. West of the Rockies, the geologic setting includes extensive basalt formations that offer unique opportunities for carbon storage, with the potential to store hundreds of years of regional CO_2 emissions.

In addition, the BSCSP land area includes vast acreage of agricultural, range, and forest lands that can be managed for greater storage of soil and biomass carbon. This region is also rich in energy resources, producing approximately 265 million megawatt hours of electricity from a variety of sources, including coal, hydroelectric power, and natural gas.

Contact

If you have any questions, comments, or would like more information about BSCSP, please contact:

Phone: 406-994-3390

BigSkyCarbon@montana.edu

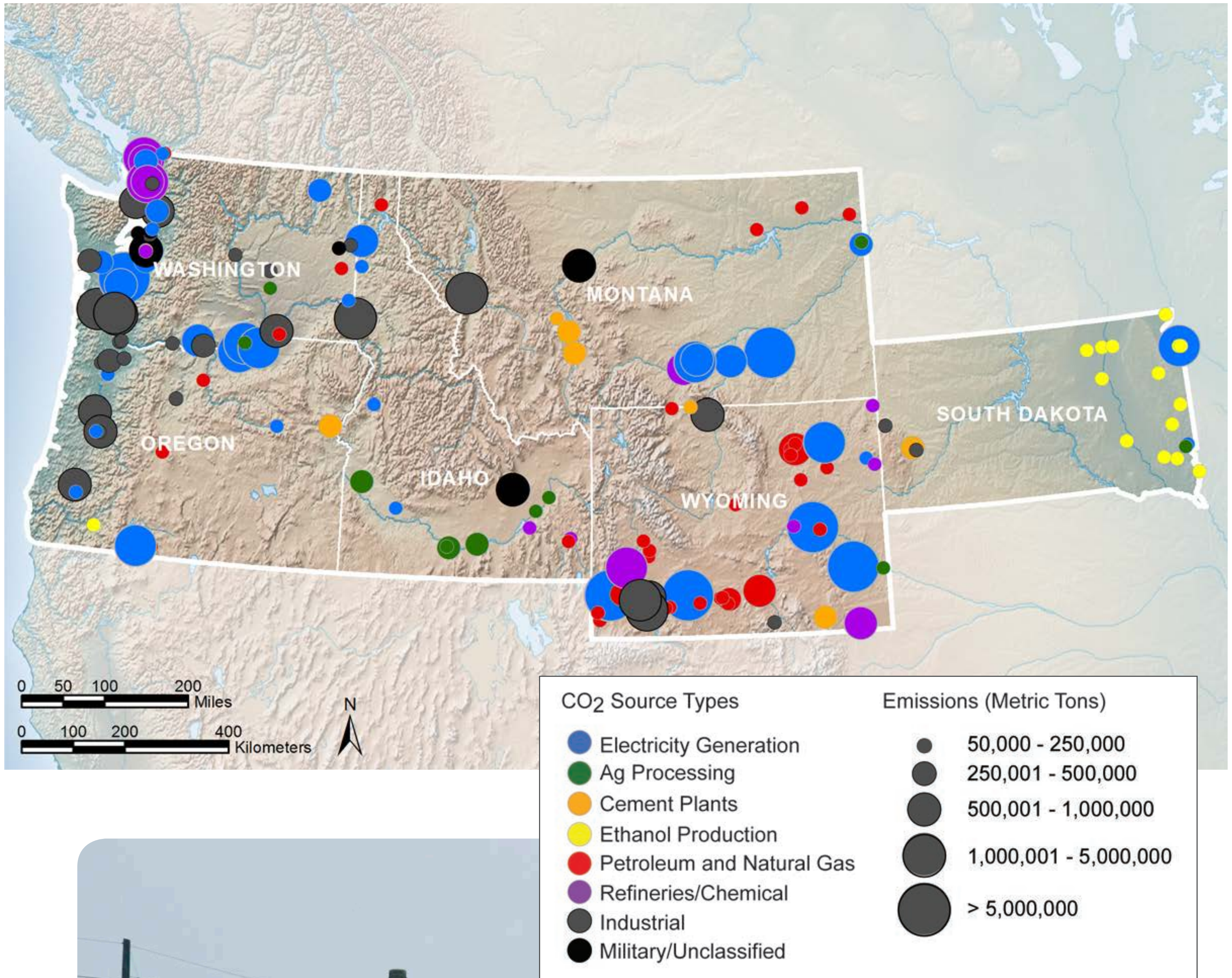
www.bigskyco2.org

BSCSP CO_2 Sources

BSCSP estimates that the region produces more than 146 million metric tons (160 million tons) of CO_2 from stationary sources each year. While the region currently produces only a fraction of national CO_2 emissions, it is home to a growing population and notable fossil energy development.

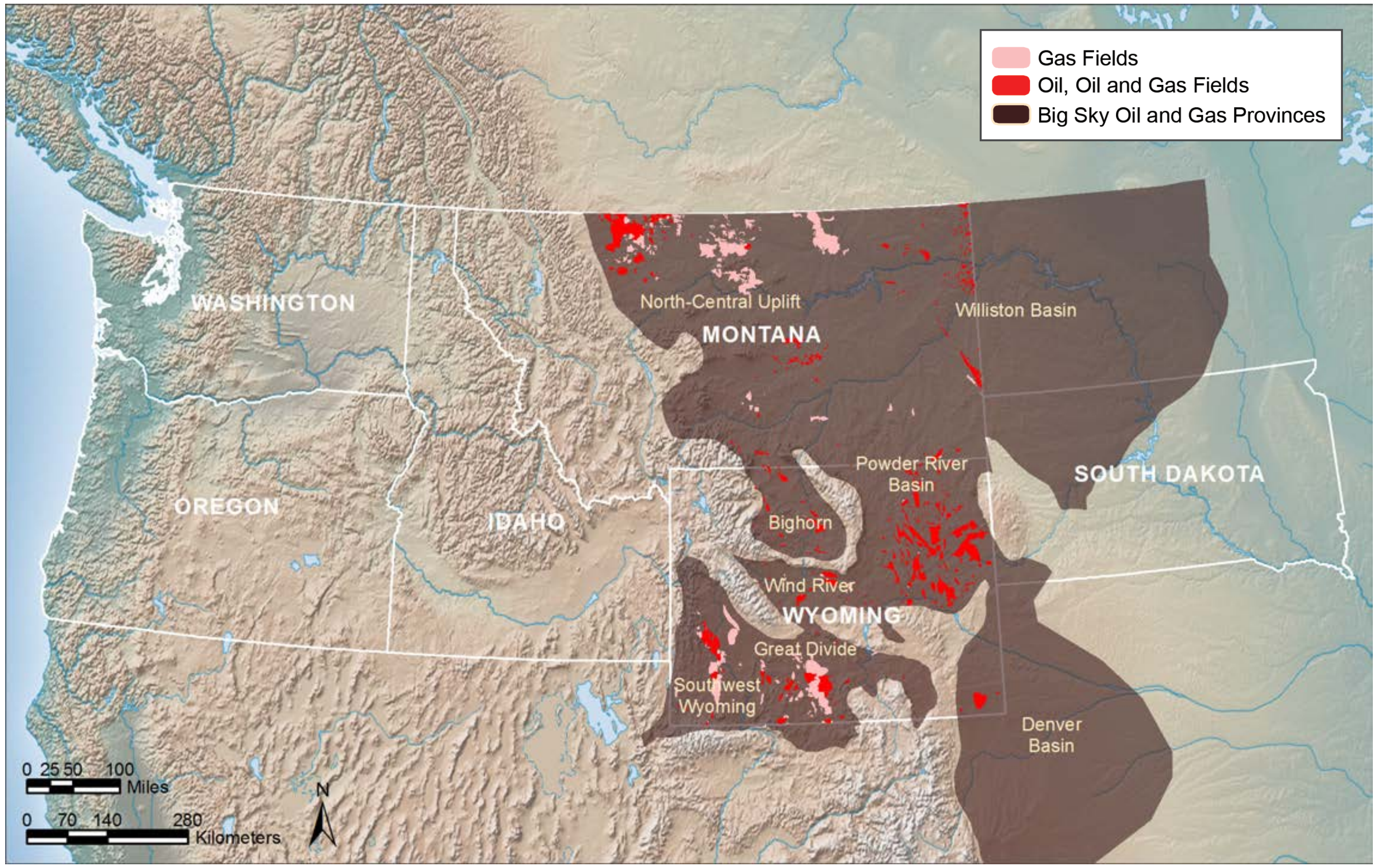
According to the 2010 U.S. Census, the region has an estimated population of 14.5 million and experienced an average growth rate of 13 percent from 2000 to 2010, with the largest growth occurring in Idaho, Wyoming, and Washington. Together, Montana and Wyoming produce two-thirds of the region's CO_2 emissions due to the high dependence on coal-fired electric generation and fossil fuel operations.

Electricity generation accounts for a large proportion (64 percent) of the region's CO_2 emissions. The region produces electricity from a variety of sources, including hydroelectric, coal, natural gas, nuclear, wind, biomass, petroleum, other gases, and geothermal. Additional sources of CO_2 emissions in the region include: industrial and manufacturing facilities (15 percent), petroleum production and transmission (5 percent), soda ash production (3.5 percent), cement production (2 percent), ethanol production (1 percent), and military operations (1 percent). Agricultural processing, ammonia production, chemical processing, and fertilizer production combined comprise less than 1 percent of the region's remaining CO_2 emissions.



Estimated CO_2 Emissions by State/Province in the BSCSP Region	
State	**Million Metric Tons**
Idaho	5,576,534
Montana	26,422,900
Oregon	15,228,870
South Dakota	6,448,512
Washington	30,000,729
Wyoming	62,675,601
Total	**146,353,146**

Corette coal plant owned and operated by PPL Montana in Billings, Montana.



BSCSP Oil and Gas Reservoirs

Mature oil and gas reservoirs in the BSCSP region have contained crude oil and natural gas for millions of years. Carbon storage capabilities of this region's depleted oil and gas reservoirs are estimated at 1.5 billion metric tons (1.65 billion tons). These reservoirs are primarily located in the sedimentary basins of Wyoming and Montana.

The major oil and gas producing regions within the BSCSP region include the (1) Williston Basin, extending across northeastern Montana and western parts of North and South Dakota; (2) Powder River Basin, spanning southeastern Montana and northeastern Wyoming; (3) Bighorn Basin in north-central Wyoming and south-central Montana; and (4) Wind River Basin in central Wyoming. Other significant oil and gas production occurs in Montana's North-Central Uplift and southwest Wyoming basins, such as the Greater Green River, Great Divide, and Hanna Basins, as well as the Wyoming Thrust Belt.

There are more than 500 active oil and gas fields in Montana and more than 1,000 active fields in Wyoming. The largest oil and gas field is located in the Powder River Basin and could potentially store 132 million metric tons (145.5 million tons) of CO_2—more than the current annual CO_2 emissions for the entire region.

Enhanced oil recovery (EOR) offers an economic incentive for carbon storage in oil and gas reservoirs. Current EOR operations within the BSCSP region include individual projects in the Green River, Wind River, and Powder River Basins that use CO_2 produced from a natural gas processing plant on the Moxa Arch in the western Green River Basin.

Pump jack in rural Montana.

Estimated CO_2 Storage Resource in Oil Reservoirs in the BSCSP Region	
State	**Million Metric Tons**
Montana	292
Wyoming	1,129
Total	**1,421**

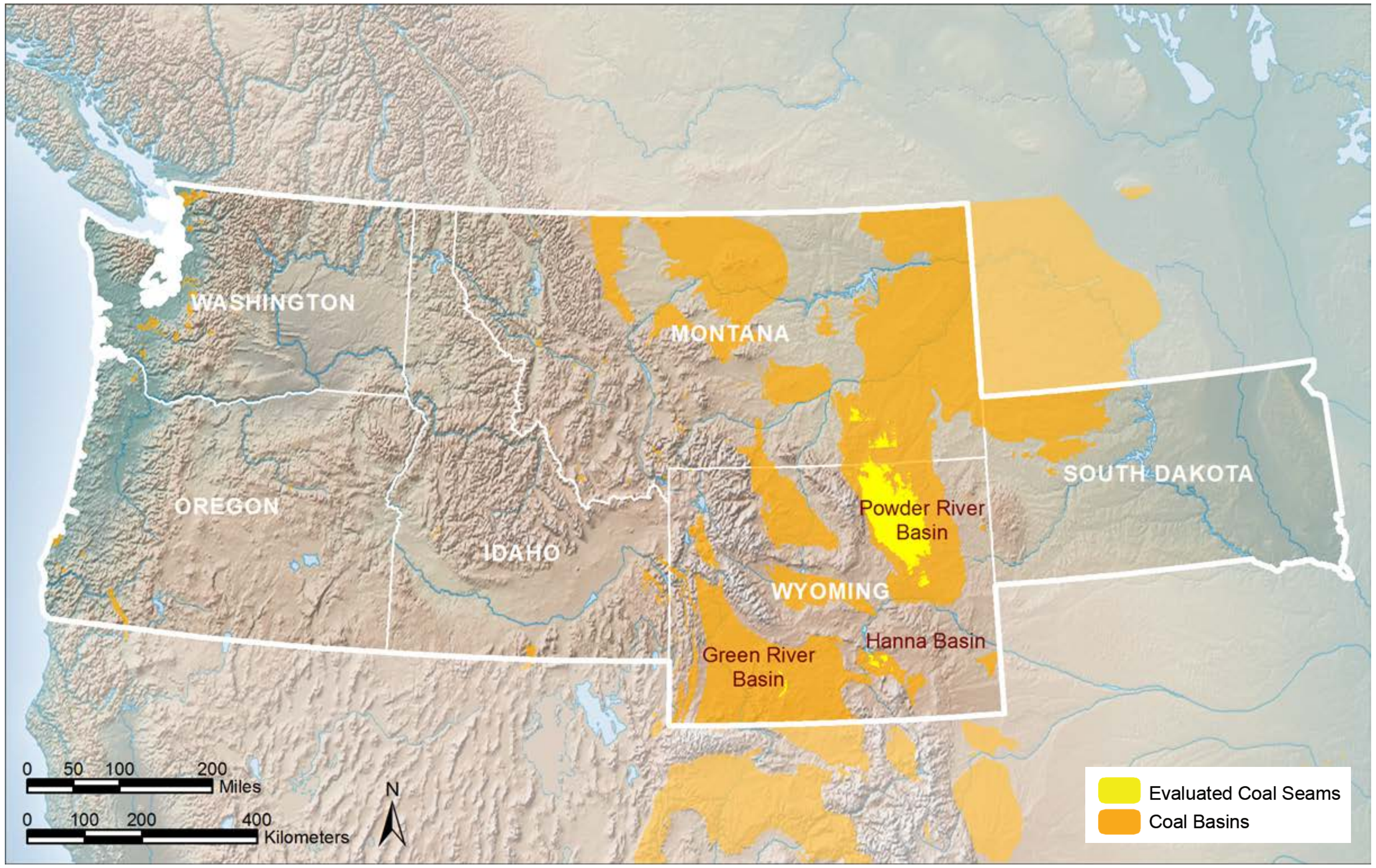
BSCSP Coal Seams

The BSCSP region contains significant coal and coalbed methane resources. Three of the largest reserves in the region include: (1) Powder River, spanning southeastern Montana and northeastern Wyoming; (2) Green River in southwestern Wyoming; and (3) Hanna in south-central Wyoming. While these are important economic resources, there is also CO_2 storage potential within coal seams that are too deep or too thin to be economically mined.

Unmineable coal is generally defined as coal buried beneath 1,000 feet or more of overburden. When CO_2 is stored in coal seams, CO_2 molecules displace methane molecules from adsorption sites within the coal matrix. The methane displaced by CO_2 can then be recovered.

The nature of the Powder River Basin coal zone makes this basin important for carbon storage in the BSCSP region. The Powder River Basin's large, unmineable coal area has an average thickness of 73 feet. The coal's high, natural permeability is essential for storing carbon given coal's tendency to swell and functionally close-off storage spaces when exposed to CO_2. The CO_2/methane displacement ratio for coal found in the Powder River Basin is much higher than other coals (more methane is produced per unit of CO_2), suggesting that the Powder River Basin may be an ideal location for carbon storage.

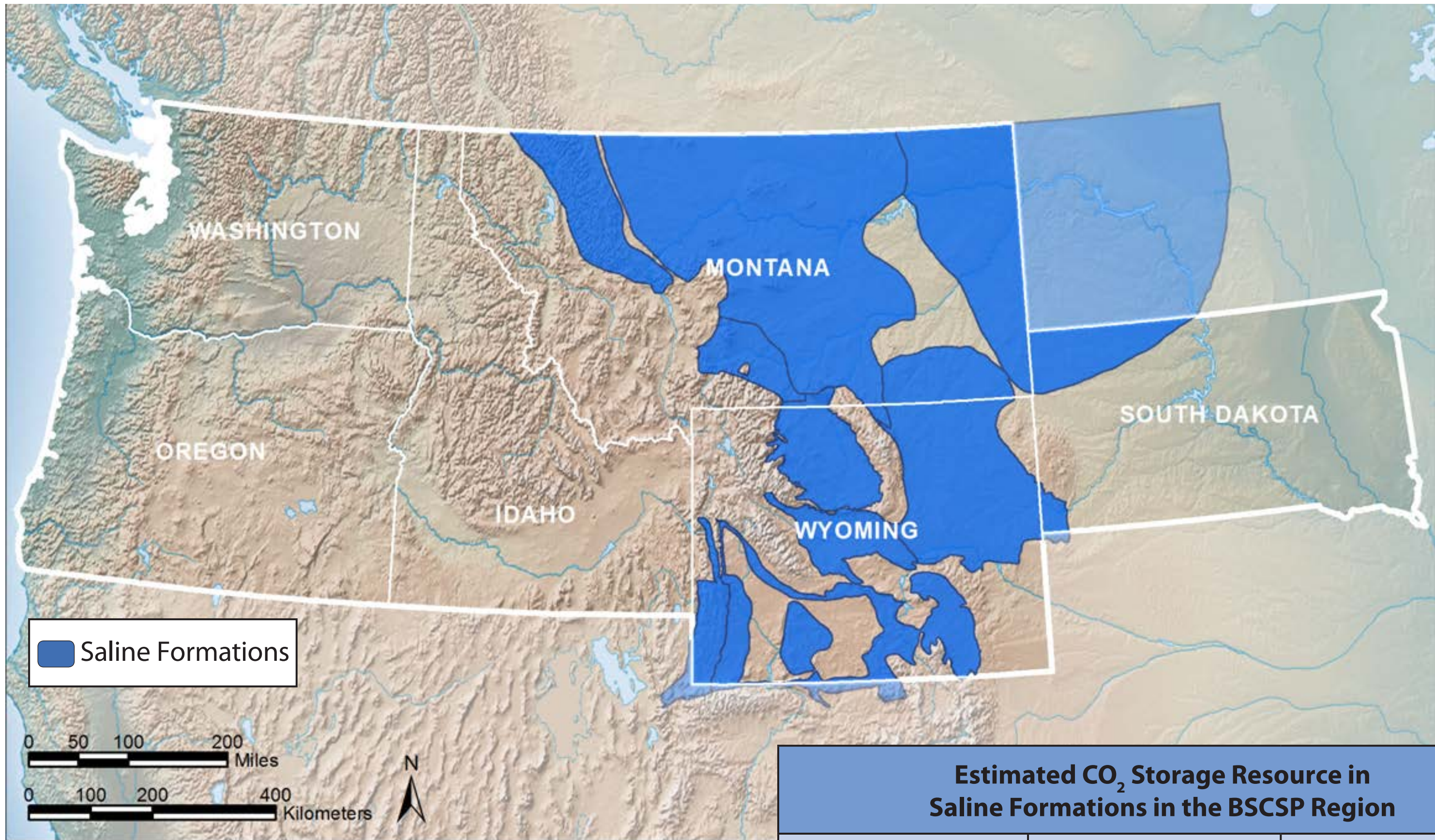
BSCSP estimates that the total CO_2 storage capacity in Powder River Basin unmineable coal seams is more than 11 billion metric tons (12 billion tons), largely due to the expansive Wyodak-Anderson coal field. Storage resource for the Green River and Hanna Basins is approximately 44 and 255 million metric tons (48 and 280 million tons) of CO_2, respectively. Although the southern Wyoming coal basins are smaller storage resources, these unmineable coal seams are economically attractive because of enhanced coalbed methane (ECBM) recovery. The production of methane from this process may help offset costs associated with CCUS.



Coal Area Storage Resources in the BSCSP Region

Basin	Coal Seam	Estimated Storage Resource (million metric tons)	
Green River Basin	Black Butte Total	28	44
	Point of Rocks Total	16	
Hanna Basin	Ferris 23 Total	9	255
	Ferris 25 Total	22	
	Ferris 31 Total	10	
	Ferris 50 Total	20	
	Ferris 65 Total	3	
	Hanna 77 Total	73	
	Hanna 78 Total	48	
	Hanna 79 Total	37	
	Hanna 81 Total	23	
	Johnson 107 Total	11	
Powder River Basin	Knobloch Total	133	11,794
	Rosebud Total	140	
	Wyodak-Anderson Total	11,522	
Partnership Total			12,093

Coal core samples.



BSCSP Saline Formations

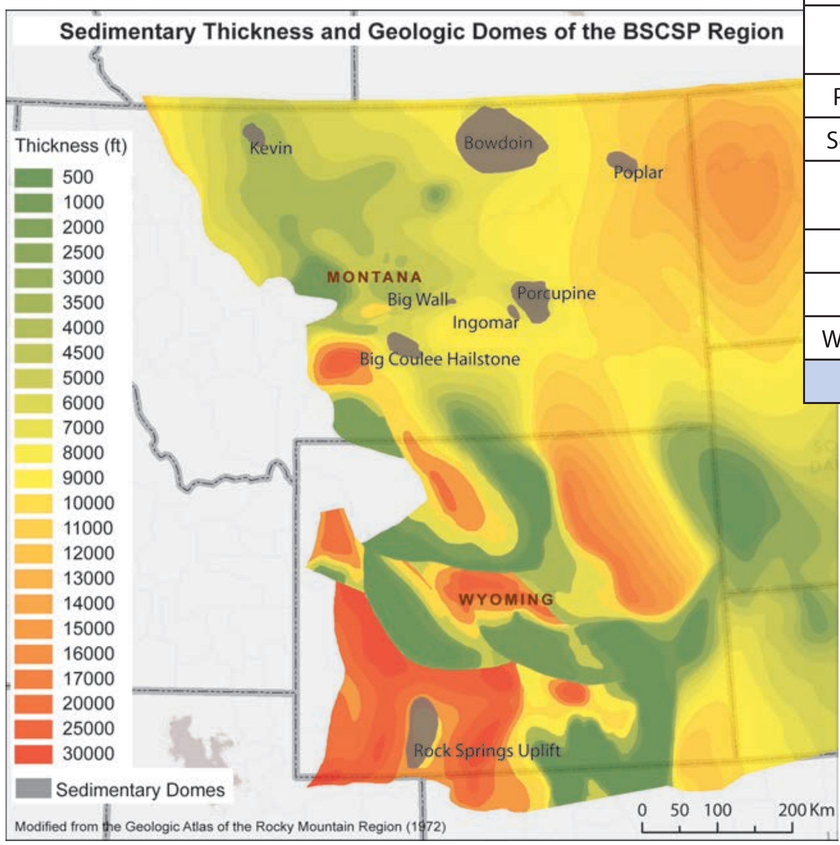
Saline formations throughout the BSCSP region offer great potential for future CO_2 storage activities. BSCSP estimates that more than 200 billion metric tons (220 billion tons) of CO_2 could be stored in the region's saline formations. The Paleozoic and Mesozoic formations of Montana and Wyoming's sedimentary basins house extensive deep saline formations, which are large enough to offset hundreds of years of manmade CO_2 emissions produced by all six states in the BSCSP region combined. The proximity of these saline formation resources to large stationary sources of CO_2 emissions, combined with existing infrastructure in the region, suggest that storing CO_2 in saline formations is both a geologically and economically viable option.

Target stratigraphic areas for CO_2 storage within the BSCSP region are dominated by porous and permeable sandstone, limestone, and dolostone. These brine-filled storage units are interbedded with evaporites and shales that create interlayered reservoir seals. Additionally, the fluid in targeted saline formations has total dissolved solids greater than 10,000 parts per million making these horizons favorable locations for carbon storage.

Some saline formations currently host vast, naturally occurring accumulations of CO_2, demonstrating the potential of these units to effectively and permanently store CO_2. BSCSP is currently conducting its Phase III project at Kevin Dome, a naturally occurring CO_2 reservoir in Montana, north of Great Falls, near the Canadian border. Kevin Dome is geologically similar to several other large structural features that occur in eastern Montana (Bowdoin Dome, Porcupine Dome, Poplar Dome, and Cedar Creek Anticline), and has successfully trapped large quantities of CO_2 for tens of millions of years. Conducting a large-scale project at the Kevin Dome will provide a better understanding of the geologic storage capabilities of this and other domes in the region.

Estimated CO_2 Storage Resource in Saline Formations in the BSCSP Region

Saline Basins	Low Estimate (million metric tons)	High Estimate (million metric tons)
Bighorn Basin	10,803	148,545
Montana Thrust Belt	2,431	33,432
North-Central Montana	67,381	926,494
Powder River Basin	14,465	198,898
Southwest Montana	2,100	28,884
Southwestern Wyoming	45,910	511,381
Williston Basin	58,375	802,668
Wind River Basin	13,658	71,015
Wyoming Thrust Belt	6,028	82,896
Total	**221,151**	**2,804,213**



Regional sandstone formation.

Regional sedimentary rock formations.

BSCSP Large-Scale Geologic Storage Field Project: Kevin Dome

BSCSP began work on a large-scale carbon storage project in northern Montana in 2011. Through this project, BSCSP aims to show that a geologic structure in Toole County, Montana, known as the Kevin Dome, is a safe and viable site to store CO_2. Kevin Dome covers approximately 700 square miles and contains a large reservoir of naturally occurring CO_2 that has been trapped in place for millions of years. The naturally occurring CO_2 is in the upper Devonian Duperow (carbonate) formation and is retained by the dome's several trapping layers.

Project Overview

BSCSP will inject 1 million metric tons (1.1 million tons) of CO_2 into the Duperow Formation and monitor it over time. BSCSP and an industrial partner plan to drill up to five wells to produce naturally occurring CO_2 from the dome. The CO_2 will then be transported in a 2-inch diameter pipeline approximately 6 miles to the injection site. From there, the CO_2 will be injected deep underground into the Duperow Formation located on the edge of the Kevin Dome. Throughout the project, scientists will closely monitor the geology, geochemistry, water quality, air quality, and CO_2 behavior. Primary MVA techniques proposed include 4-D seismic surveying, geochemical sampling, and pressure monitoring, along with other techniques.

Seismic trucks used to generate 4-D data of subsurface.

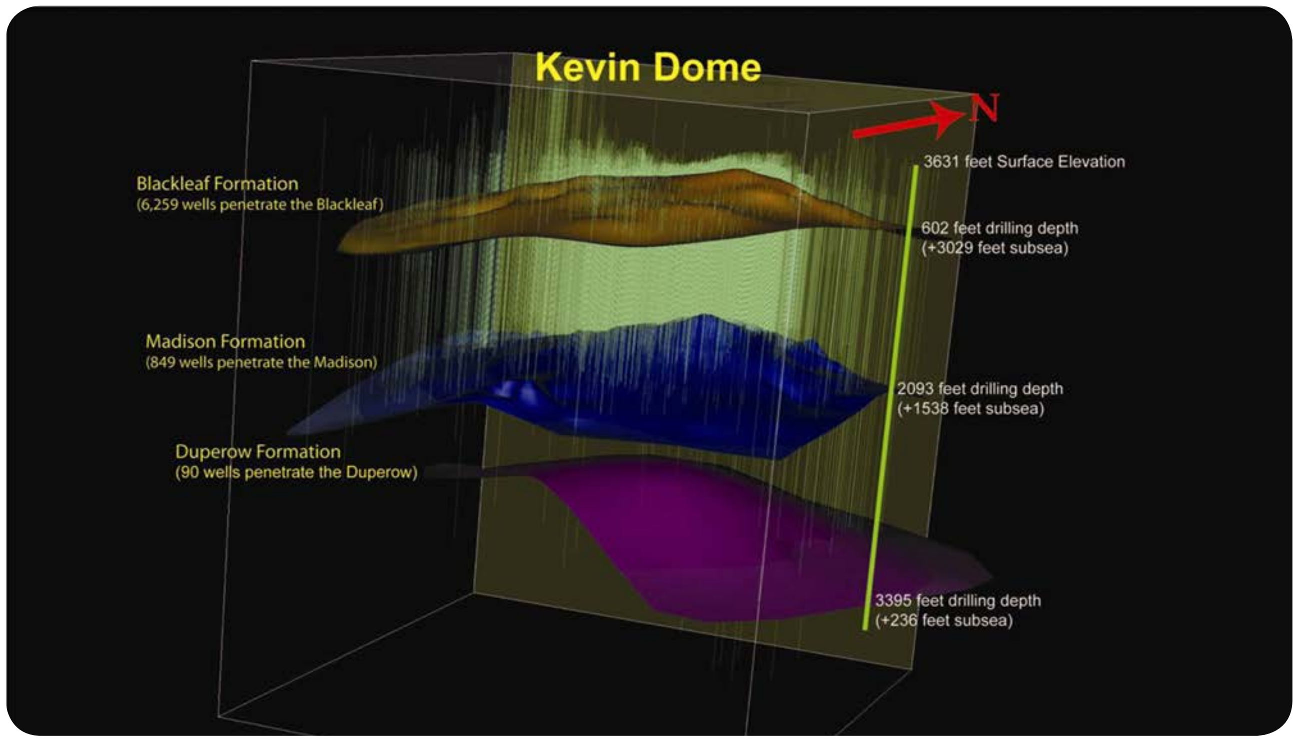
Instrumentation used to align seismic components in the field.

Project Objectives

The project objectives include improved understanding of: (1) the potential of domes for geologic storage and to account for the stored CO_2; (2) the evaluation and comparison of geochemical changes in reservoir rocks exposed to CO_2 for millennia, as well as recently exposed rocks; (3) geomechanical and geophysical characteristics of caprocks in naturally occurring reservoirs; and (4) the evaluation of stacked storage and detection of a smaller pool of CO_2 stored above a larger volume.

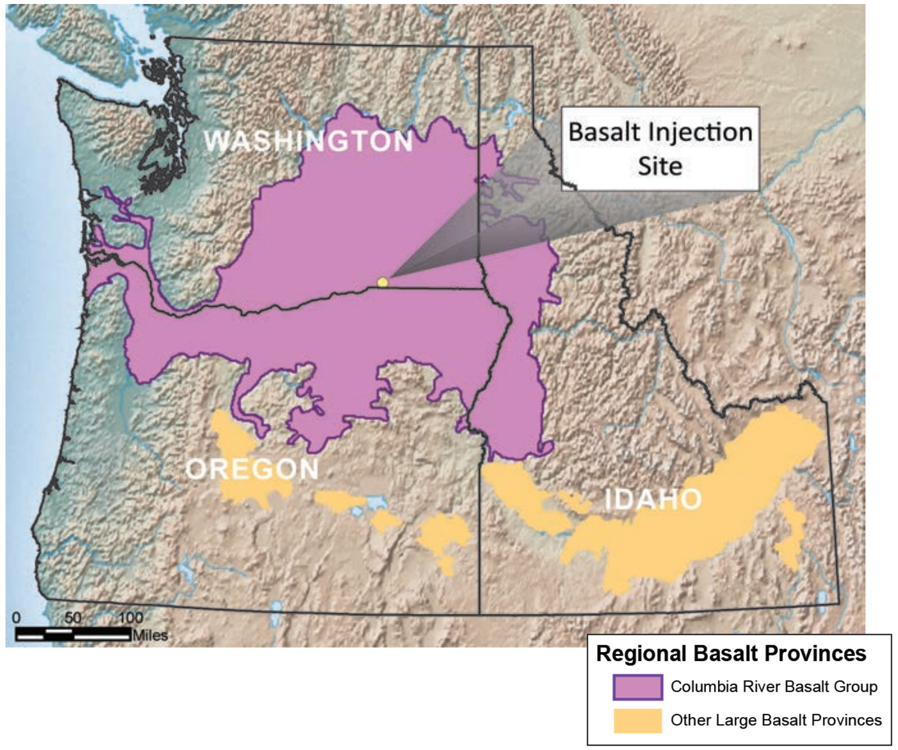
Project Status

BSCSP is currently securing necessary Federal and state permits, refining geologic models, and conducting geophysical surveys for the project. BSCSP plans to drill the wells in 2013. Injection is planned to begin in 2014 and continue for 4 years; post-injection monitoring will take place for an additional time period.



Initial geological model of Kevin Dome layers.

BSCSP Basalt Formations



Basalt outcrop near small-scale field site.

Igneous rock formations.

Basalt core sample.

Rock samples from Validation Phase project.

Basalt formations are prevalent in the BSCSP region and may play an important role in geologic storage because of their unique properties. These formations are globally distributed and could significantly expand CO_2 storage options in regions where other geologic storage options are limited or non-existent.

In the BSCSP region, the Columbia River Basalt Group covers approximately 63,300 square miles and has been thoroughly studied by researchers. These large basalt provinces were formed millions of years ago as lava flows cooled on the Earth's surface. As successive flows cooled over time, layers of basalt were formed, each tens to hundreds of feet thick. The exterior portions of each layer cooled quickly, forming cracks and bubbles, while the interiors cooled slowly, creating dense and impermeable layers. The dense interior sections serve as caprocks while the porous exterior sections serve as potential injection zones for CO_2 storage.

Laboratory tests have shown that basalts are geochemically reactive and can chemically trap CO_2. When basalts have been exposed to dense phase CO_2 and water in a lab setting, minerals in the basalt react with the CO_2 and water to form limestone or calcium carbonate. This geochemical process traps the CO_2 in a solid form and permanently isolates it from the atmosphere. Similar mineralization processes happen in other rock types but at much slower rates.

BSCSP is working with local partners and Battelle Pacific Northwest National Laboratory to conduct a small-scale geologic storage test in southeast Washington State. This project is one of the first in the world to examine both the viability and capacity of deep basalt formations and will expand laboratory findings to in-situ environments. By assessing the technical issues associated with injection, fate, and transport of CO_2, scientists aim to verify that these basalts are safe and practical sites for large-scale CO_2 storage activities.

Integrating CCUS into the BSCSP Community

BSCSP is involved in a wide range of education and outreach activities to engage stakeholders and expand the understanding of CCUS science and projects in the region.

Objectives

The primary objectives of the BSCSP Outreach Program are to: (1) provide information on regional carbon storage opportunities; (2) inform and engage the public in projects and regional characterization efforts; (3) facilitate communication and collaboration among stakeholders; and (4) enhance CCUS education. Outreach materials include webpages, workshops, annual meetings, outreach surveys, films, newsletters, and other community engagement efforts.

Small-Scale Project

BSCSP provides both internal and external outreach to support the large-scale project and improve the understanding of CCUS in general. BSCSP has held several meetings in host communities and distributed several project factsheets, newsletters, and press releases. These efforts have fostered relationships with local residents, increased local knowledge of the project, and improved community relations.

BSCSP Annual Meeting

BSCSP hosts a 2-day conference on BSCSP projects and related topics each year. The meeting includes presentations by speakers from across the nation, covering the science, policy, and technology of CCUS. This event is attended by academics, industry professionals, environmental nonprofit staff, elected officials, ranchers, small-business owners, and students.

Educational Workshops & Resources

BSCSP works to support teachers, students, local landowners, and other stakeholders who wish to learn more about the latest CCUS science. BSCSP also engages with legislators, local officials, committees, and staffers in the BSCSP region. These activities are carried out through presentations in state capitols and technical information materials for policy makers.

Site visit to Wallula, Washington.

BSCSP Annual Meeting in Great Falls, Montana.

Regional wildlife includes pronghorn and migratory birds.

BSCSP Permitting and Regulations

Permitting and regulatory compliance are important components to the overall success of carbon storage efforts in the BSCSP region. BSCSP has initiated the permitting process and is working with the appropriate Federal and state agencies to obtain all permits necessary for the Kevin Dome Carbon Storage project in Montana. The permitting process is designed to evaluate the project and potential ties to the surrounding environment, such as air quality, geology and soils, water resources, wetlands and floodplains, vegetation and wildlife, land use, socioeconomic resources, human health and safety, cultural resources, and waste management issues. Permissions are also obtained from landowners for surface access, site development, and other related activities.

Regulations

Regulatory compliance for the project includes adherence to the National Environmental Policy Act, the Montana Environmental Policy Act, and various other Federal and state regulations. Project activities that require permits include seismic surveying, well drilling, pipeline and compressor station construction, CO_2 injection, operations, and monitoring activities.

Legislation

In the 2009 Legislative Session, Montana legislators passed Senate Bill 498 to regulate carbon storage in Montana. Senate Bill 498 designated regulatory oversight to the Montana Board of Oil and Gas, in consultation with the Montana Department of Environmental Quality. Together, these entities are working to develop specific rules for carbon storage in Montana.

Pore space for carbon storage is also defined in this bill and is assigned to the surface owner. Finally, the bill determines that prior to project completion and transfer of title, the operator is liable for the operation and management of the CO_2 injection well, the storage reservoir, and the injected or stored CO_2. The operator must furnish an adequate bond or other surety to guarantee that all state requirements are met. The completion and transfer of ownership and liability from the operator to the state is a process that takes 30 years.

Senate Bill 498 formally takes effect when the Montana Board of Oil and Gas is granted primacy for CO_2 injection wells by the U.S. Environmental Protection Agency EPA). This approval is expected to take place in 2015. Until then, the EPA will permit and regulate injection of CO_2 under the Underground Injection Control Program.

Several permits are required for seismic activities.

Federal Agencies/Entities
U.S. Department of Energy
U.S. Environmental Protection Agency
U.S. Bureau of Land Management
U.S. Fish and Wildlife Service
U.S. Department of Transportation
U.S. Army Corps of Engineers
Native American Tribal Governments

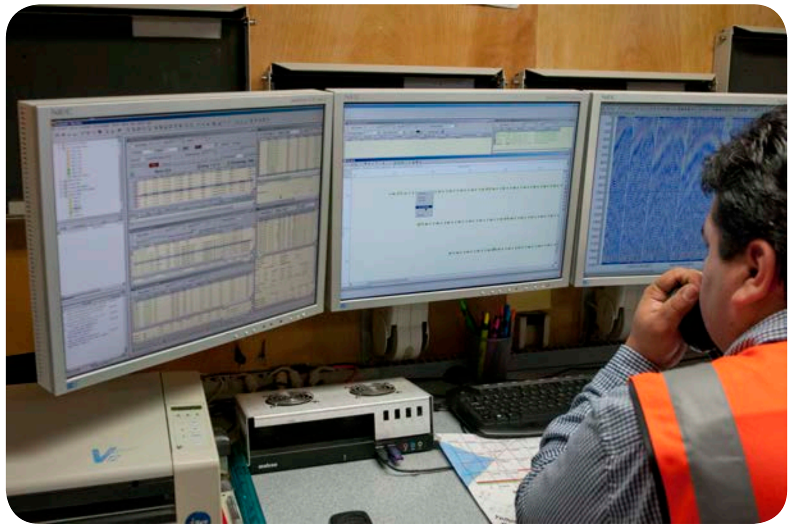
State Agencies
Montana Department of Natural Resources Conservation
Montana Department of Environmental Quality
Montana Board of Oil and Gas

BSCSP Monitoring, Verification, and Accounting Activities

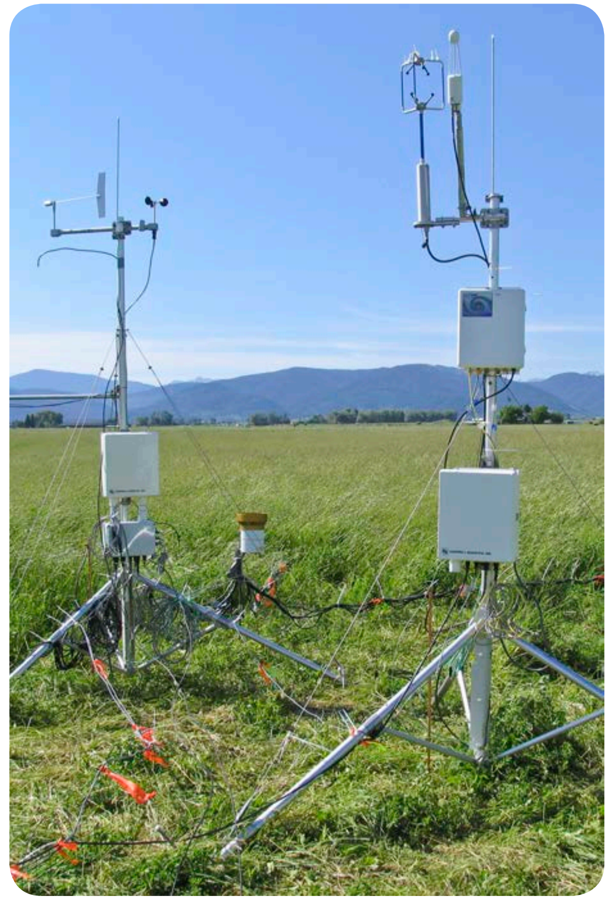
Monitoring, verification, and accounting (MVA) activities are an integral part of CCUS field projects in the BSCSP region. BSCSP has developed a comprehensive monitoring program for the large-scale geologic storage project. This program incorporates geophysical, geochemical, surface, and other monitoring methods that will be implemented before, during, and after injection activities. This approach allows scientists to compare changes over space and time.

Potential surface detection methodologies include eddy-covariance towers, flux chamber measurements, LIDAR, and hyperspectral imaging (or other methods of measuring vegetation changes), as well as traditional soil gas analysis to establish background CO_2 levels. Efficacy of specific methods will depend on topology, prevailing winds, plant ecology, and similar factors. The Kevin Dome Carbon Storage project site is expected to have large seasonal variation; thus, baseline measurements will start at least 1 year prior to injection and serve as a comparison for later data. In addition, measurements of tracer systems will be taken before, during, and after CO_2 injection to monitor CO_2 movement in the subsurface.

To monitor the subsurface, a 3-D, nine-component seismic survey will be conducted prior to injection in order to properly characterize the target formation and seals, and to determine optimum placement of the production wells, injection well, and monitoring wells. The results of the survey will be incorporated into the static geologic model. A second 3-D, nine-component seismic survey will be conducted post injection to facilitate a composite 4-D seismic survey that includes changes over time. Baseline measurements of geochemical and geophysical properties will be acquired using downhole techniques during or after drilling and before injection. Reservoir condition evaluation and plume monitoring techniques will likely include vertical seismic profilings, cross well seismic profiling, a modern logging suite, additional surface geophysical surveys, and fluid geochemical analysis.



Field crews closely monitor data collection in real time.



Eddy-covariance towers collect environmental data from the field. (Photo courtesy of Jennifer Lewicki)

Soil gas chambers analyze CO_2 levels in the soil. (Photo courtesy of Jennifer Lewicki)

Midwest Geological Sequestration Consortium

The Midwest Geological Sequestration Consortium (MGSC) is a consortium of the geologic surveys of Illinois, Indiana, and Kentucky joined by private corporations, professional business associations, the Interstate Oil and Gas Compact Commission, three Illinois state agencies, and university researchers to assess carbon capture, transportation, and geologic storage processes and their costs and viability in the Illinois Basin region. The Illinois State Geological Survey is the Lead Technical Contractor for MGSC, which covers all of Illinois, southwest Indiana, and western Kentucky.

To avoid atmospheric release of CO_2 from fossil fuel combustion, and thereby reduce the potential for climate change, MGSC is investigating options for geologic CO_2 storage in the 155,400-square-kilometer (60,000-square-mile), oval-shaped geologic feature known as the Illinois Basin. Within the basin there are deep, uneconomic coal resources; numerous mature oil fields; and deep saline formations with potential to store CO_2. MGSC's objective is to determine the technical and economic feasibility of using these geologic formations for long-term storage.

The Illinois Basin is geologically unique because all three potential geologic storage opportunities exist in close proximity to substantial CO_2 sources and, in some cases, may be accessed from one site.

Typical central Illinois Basin landscape.

Contact

If you have any questions, comments, or would like more information about MGSC, please contact:

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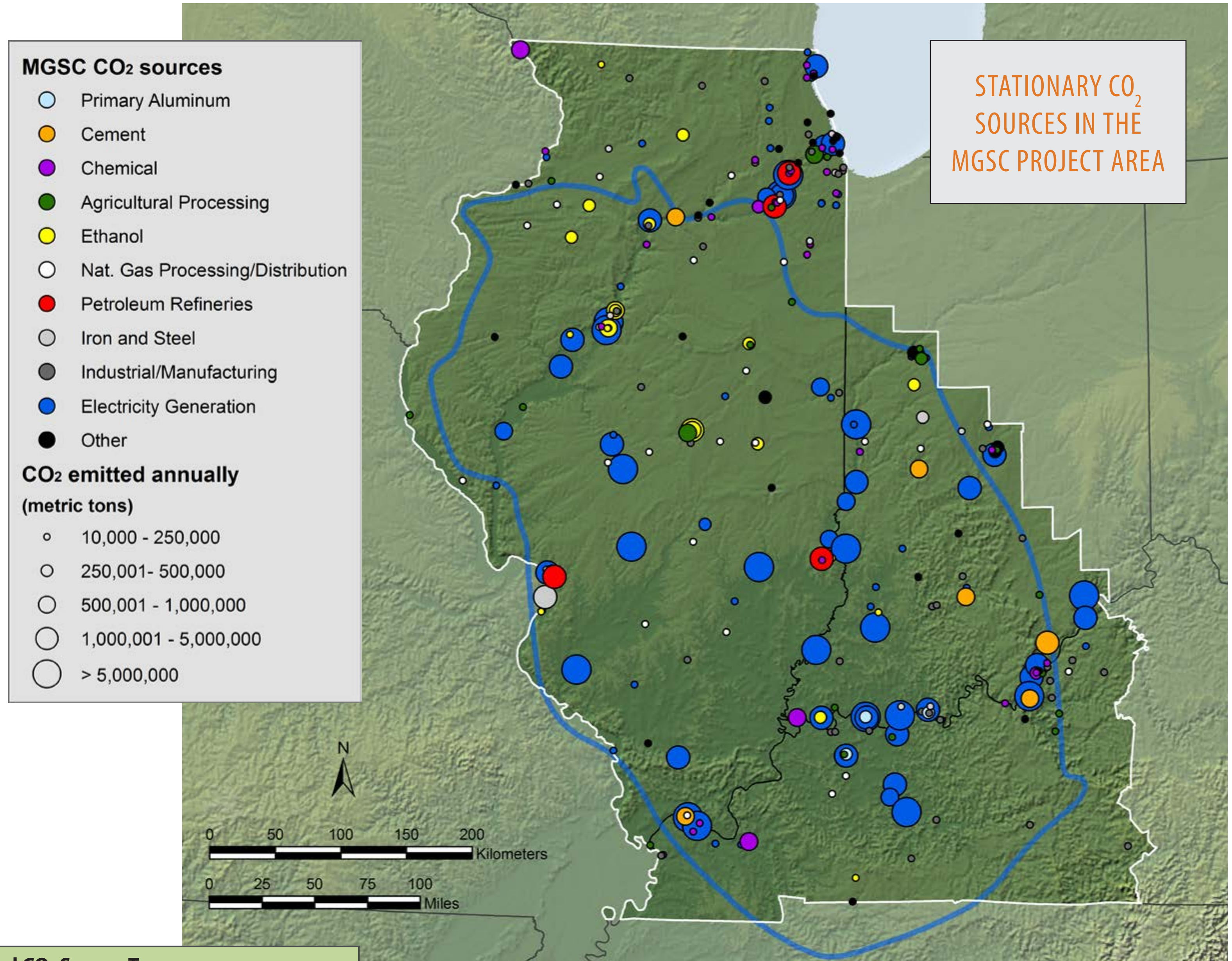
MGSC CO_2 Sources

The Illinois Basin region has annual CO_2 emissions exceeding 291 million metric tons (321 million tons), with a carbon equivalent of 80 million metric tons (88 million tons) from major industrial stationary sources emitting more than 10,000 metric tons (11,023 tons) per year.

Coal-fired electricity generation facilities are the most dominant fixed sources, some of which burn almost 4.5 million metric tons (5 million tons) of coal per year. The distribution of emissions from these plants is highly skewed. The five largest plants, in terms of CO_2 emissions, emit approximately 25 percent of total CO_2 emissions; the 15 largest plants emit greater than 50 percent of total CO_2 emissions; and the 30 largest plants emit approximately 70 percent of total CO_2 emissions. In recent years, the Illinois Basin region has contributed approximately 11 percent of the total U.S. CO_2 emissions from electric power generation plants. Coal is the dominant fossil fuel for these electricity generation plants and contributes over 95 percent of the Illinois Basin CO_2 emissions from stationary sources of electricity.

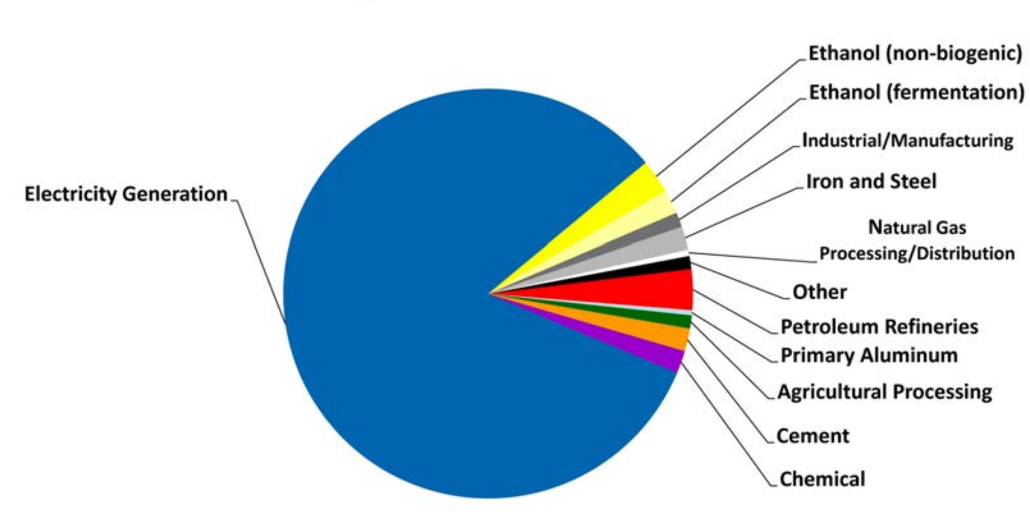
Carbon dioxide emissions from the commercial/manufacturing sector vary from industry to industry and account for approximately 17 percent of the total tabulated emissions in the Illinois Basin region.



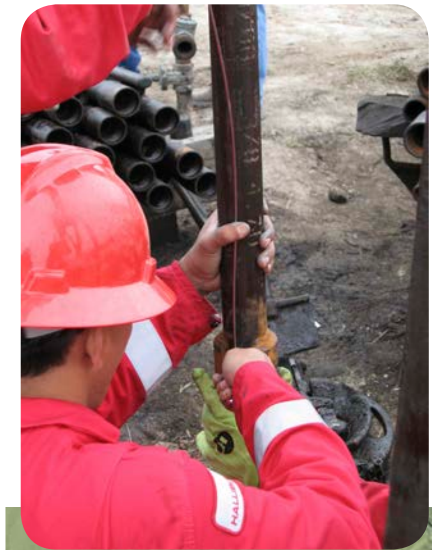
Illinois Basin (MGSC) CO_2 Emissions by State and CO_2 Source Type				
Source Type	Illinois Basin Annual CO_2 Emissions (million metric tons)			
	Illinois	Southwest Indiana	Western Kentucky	Total
Primary Aluminum	0.0	0.4	0.7	1.1
Cement	1.6	2.8	0.8	5.2
Chemical	2.9	1.0	1.3	5.2
Agricultural Processing	2.3	0.6	0.2	3.1
Ethanol (non-biogenic CO_2)	7.3	0.5	0.1	7.8
Ethanol (fermentation*)	4.8	0.7	0.1	5.5
Nat. Gas Processing/Distribution	1.1	0.2	0.1	1.4
Petroleum Refineries	9.2	0.2	0.0	9.4
Iron and Steel	4.6	0.7	0.0	5.3
Industrial/Manufacturing	1.4	0.4	1.6	3.4
Electricity Generation	97.7	88.2	54.9	240.8
Other	1.3	1.4	0.3	3.0
Total	**134.2**	**97.1**	**60.1**	**291.2**

*Ethanol fermentation CO_2 emissions estimated from production capacity.

MGSC CO_2 Stationary Source Emissions by Type



MGSC Oil and Gas Reservoirs



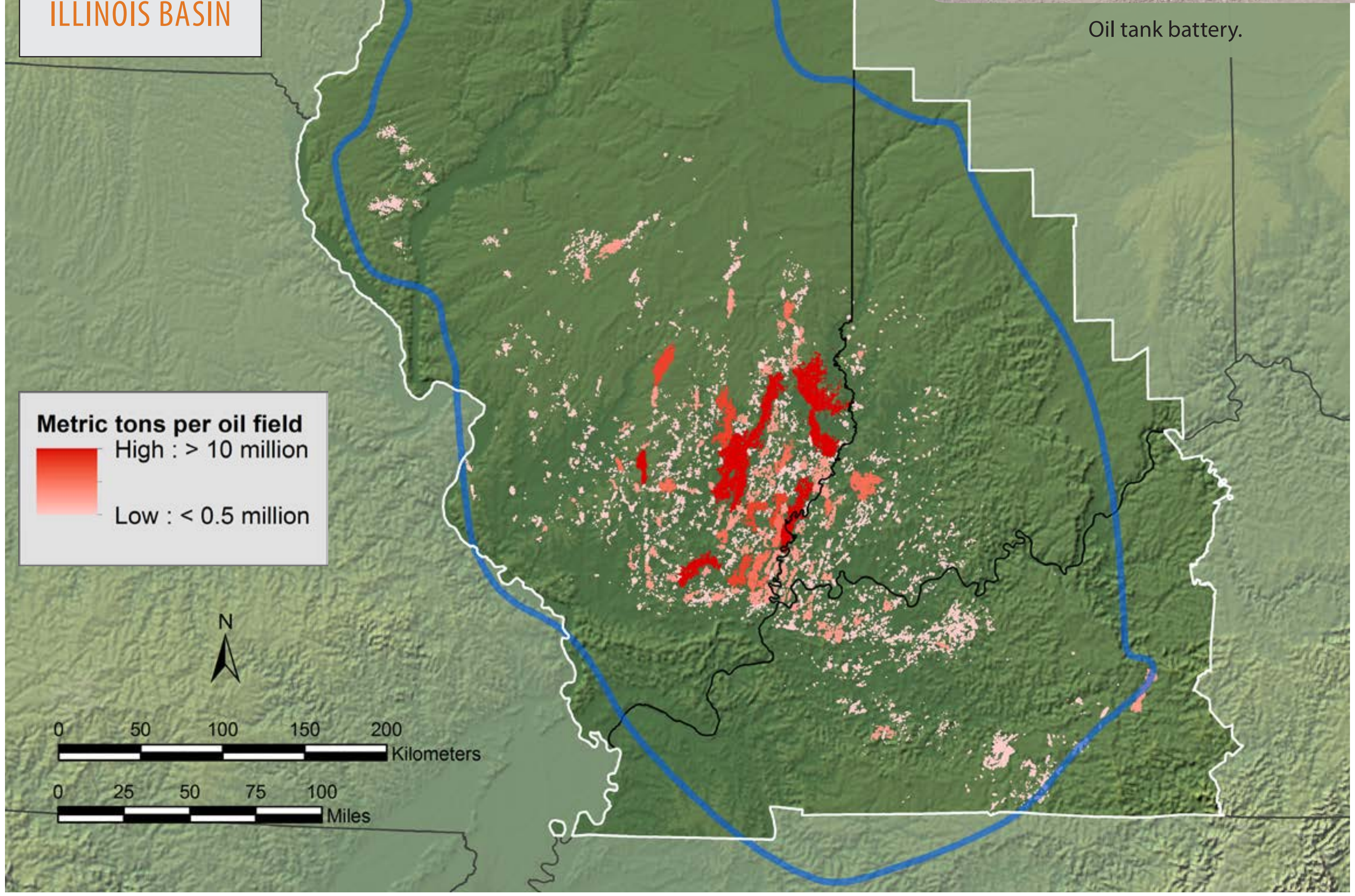
Installation of downhole pressure sensor.

State	CO_2 Storage Resource (million metric tons)	Estimated EOR* (million barrels)
Illinois	106 to 358	632 to 979
Indiana	20 to 47	124 to 162
Kentucky	14 to 35	104 to 138
Total	**140 million to 440 million metric tons**	**860 million to 1.3 billion barrels**

* The EOR volume was estimated based on a series of oil recovery factors for specific geologic units and miscibility type that were applied to the original oil in place as assessed per oil field.

Oil production well.

Oil tank battery.



Oil reservoirs offer the most potential to economically offset the costs associated with carbon storage in the Illinois Basin. To assess this potential, a basin-wide EOR estimate was made based on the original oil in place in the basin, the CO_2 storage resource, the assessed EOR resource, the geographic and geologic distribution of EOR potential, and the type of recovery mechanism (miscible vs. immiscible). The resource target for EOR in the Illinois Basin is 137 million–207 million cubic meters (860 million–1,300 million barrels) recoverable oil, with a consequent storage resource of 140 million–440 million metric tons (154 million–485 million tons) of CO_2.

Cumulative oil production for the Illinois Basin is approximately 0.67 billion cubic meters (4.2 billion barrels), and nearly 1.5 billion cubic meters (10 billion barrels) of oil remain primarily as unrecovered resources in known oil fields. To assess the recovery potential of a part of this resource and the concurrent stored CO_2 volumes, geologic modeling and compositional reservoir simulation were carried out. Parts of nine fields were used to create general purpose geologic models for the most prolific oil-bearing reservoirs in the basin: the Aux Vases and Cypress Sandstones and the St. Genevieve Limestone. These models incorporated data from more than 1,000 total wells, 120 wells with core, more than 2,000 core sample points, 12,000 field acres, and 20 flow zones. Structure and isopach maps were developed from well logs, whereas porosity and permeability distributions were geostatistically developed from core analysis data for use in the reservoir simulator. Processes simulated included miscible and immiscible flooding based on reservoir pressure and temperature and both continuous and water-alternating-gas CO_2 injection scenarios.

An important step in improving the methodology to estimate CO_2-EOR and storage in oil reservoirs would be screening tools that include economic and basin-specific issues that may be necessary to implement a CO_2-EOR flood. To better understand these aspects, a new study is underway that is developing general CO_2-EOR performance curves reflective of Illinois Basin geologic formations, calibrating the curves via rigorous geologic and reservoir models, and combining the results with an economic study of the capital and operating expenses of surface facilities.

MGSC Unmineable Coal and Organic-Rich Shale Basins

Unmineable Coal

The Illinois Basin holds substantial remaining coal resources, totaling 258 billion metric tons (284 billion tons). Coal production in the Illinois Basin has grown steadily since 2003, and this trend is projected to continue. For this Atlas, coals were considered to be unmineable if they were thinner and/or deeper than coal currently or previously mined. The opportunity to store CO_2 in coalbeds is based on both technical and economic considerations that could be supported by the production of coalbed methane displaced from these coals.

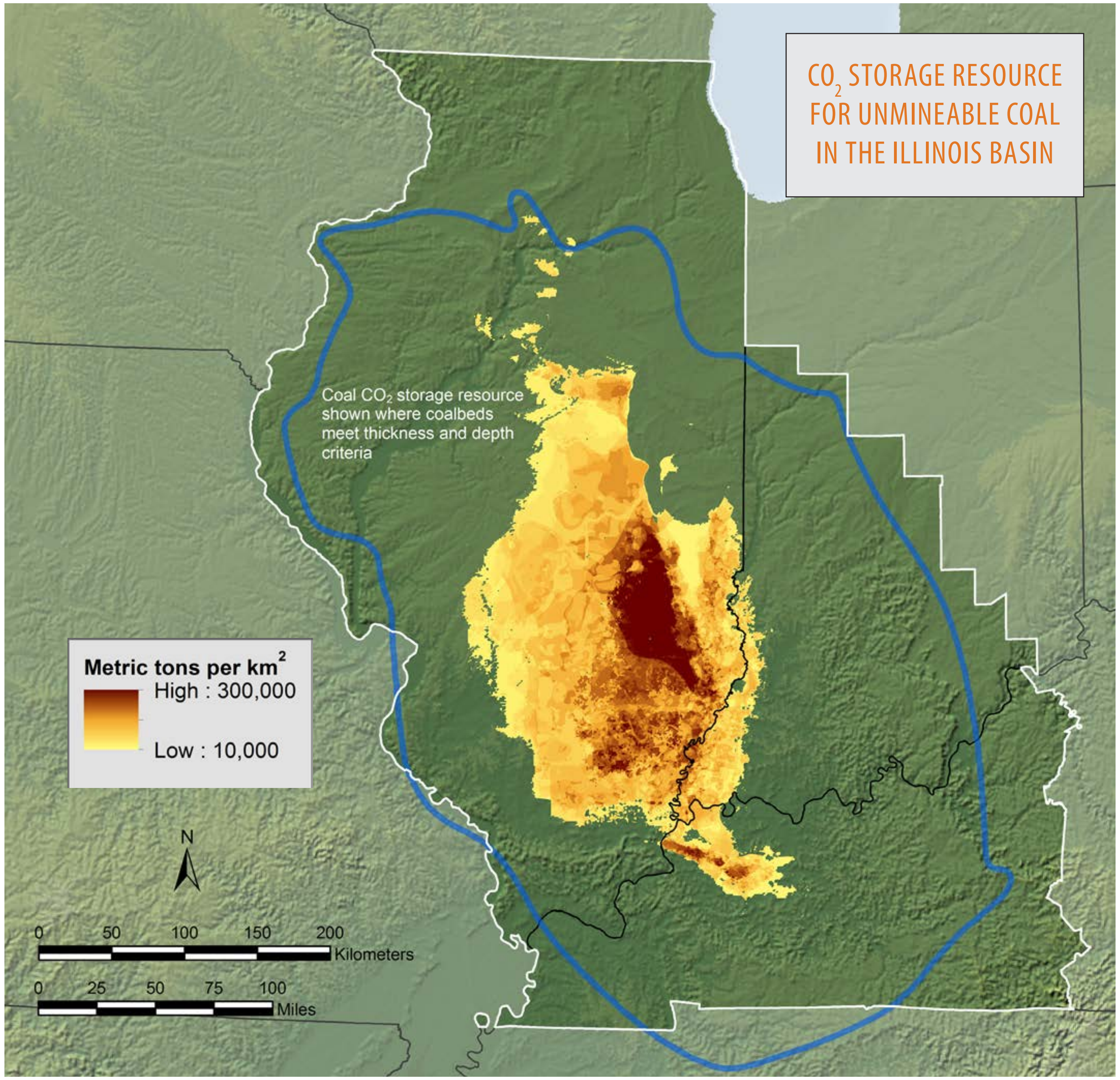
Coalbed methane gas contents for Illinois Basin coals range from 3.12 to 4.68 cubic meters per metric ton (100 to 150 standard cubic feet per ton). CO_2 adsorption can range from 14.1 to 21.9 cubic meters per metric ton (450 to 700 standard cubic feet per ton) at 2,068 kiloPascals (300 pounds per square inch). Using a geographic information system-based volumetric methodology, seven major coals were mapped and assessed throughout the Illinois Basin, with the latest storage efficiency factors yielding a total CO_2 storage resource estimate of 1.6 to 3.2 billion metric tons (1.8 to 3.5 billion tons).

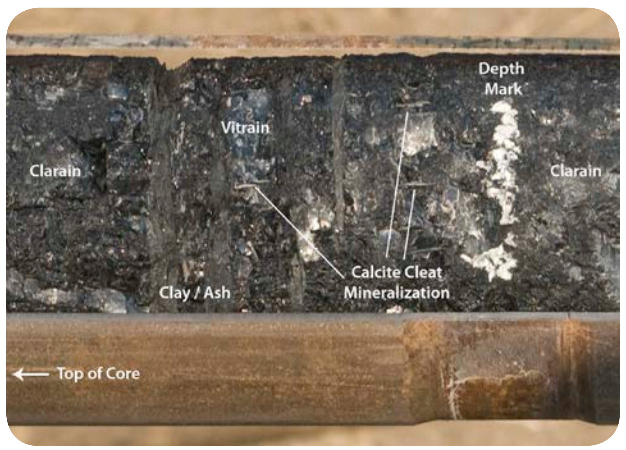
Organic-Rich Shale

The New Albany Shale is a black, organic-rich shale and a commercially productive gas reservoir in Indiana and Kentucky. Preliminary isotherm adsorption data from several wells, including the Blan Well in Hancock County, Kentucky, suggest that the shale can adsorb CO_2 in the range of three to four times the equivalent amount of methane.

The total organic carbon content of shale is directly related to CO_2 adsorption, and recent work has identified specific areas in the New Albany Shale that might have high total organic carbon and be potential storage sites, particularly in the eastern part of the basin. Further site-specific evaluation is necessary to explain these high total organic carbon values and their relation to storage potential.

Initial volumetric estimates indicate that up to 15 billion metric tons (17 billion tons) of CO_2 could be stored in the organic-rich shale of the Illinois Basin. Estimates are being further refined based on the distribution and quantity of organic matter in the shale, level of thermal maturity, low permeability and rate of CO_2 injection, chemical reactions between the oxidizing fluids and the inorganic portion of the shale, variations in shale lithology, and displacement efficiencies. The New Albany Shale is the primary seal for Silurian and Devonian oil and gas reservoirs and may act as a secondary seal for storage in deeper Paleozoic reservoirs, such as the Mt. Simon and St. Peter Sandstones.



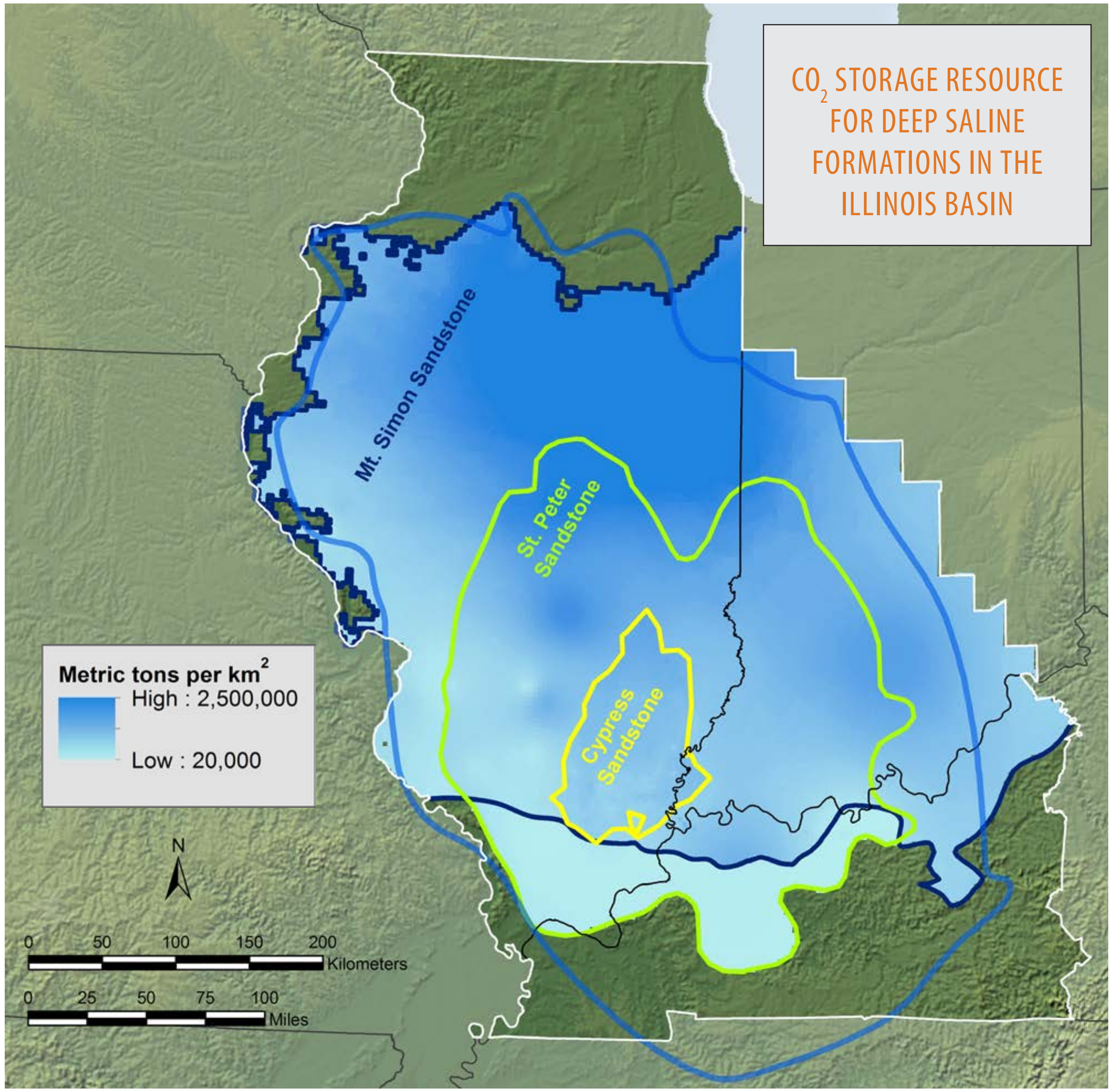


Banded horizons in Springfield Coal core. Core was drilled vertical and is shown rotated 90 degrees.

State	CO_2 Storage Resource* (million metric tons)	Estimated ECBM** (billion scf)
Illinois	1,470 to 2,900	2,700 to 9,800
Indiana	86 to 170	150 to 600
Kentucky	68 to 134	130 to 470
Total	**1.6 billion to 3.2 billion metric tons**	**3.0 trillion to 10.9 trillion scf**

* Using storage efficiency (E) factors of 39% and 77%, respectively, which represent the P_{10} and P_{90} estimates.

**Enhanced coalbed methane was estimated based on a methane recovery factor that was applied to the original gas-in-place volume per coal seam for unmineable coal areas as described above.



Reservoir	CO_2 Storage Resource* (billion metric tons)
Cypress Sandstone	0.2 to 2.3
St. Peter Sandstone	0.4 to 5.9
Mt. Simon Sandstone	11 to 150
Total	12 billion to 158 billion metric tons

* Using storage efficiency (E) factors of 0.4% and 5.5%, respectively, which represent the P_{10} and P_{90} estimates. Figures have been rounded.

State	CO_2 Storage Resource* (billion metric tons)
Illinois	8.3 to 114
Indiana	2.8 to 39
Kentucky	0.4 to 5.1
Total	12 billion to 158 billion metric tons

* Using storage efficiency (E) factors of 0.4% and 5.5%, respectively, which represent the P_{10} and P_{90} estimates. Figures have been rounded.

MGSC Saline Formations

Four saline reservoirs in the Illinois Basin are being studied for CO_2 storage potential: the Mississippian Cypress Sandstone, the Ordovician St. Peter Sandstone, the Cambro-Ordovician Knox Supergroup, and the Cambrian Mount Simon Sandstone.

The Cypress Sandstone is the most widespread and prolific petroleum-bearing sandstone in the Illinois Basin; however, areas with thick Cypress tend to have a large water-bearing zone that may be considered for saline storage. The porous and permeable sandstone can reach a thickness of 60 meters (200 feet), although it is generally less than 30 meters (100 feet) thick and displays considerable variation in thickness and lateral extent. It is the shallowest of the saline reservoirs assessed and is found at depths reaching approximately 900 meters (3,000 feet) in parts of the Illinois Basin. Shale beds and a laterally continuous carbonate, the Beech Creek (Barlow) Limestone, form the overlying seal for the Cypress Sandstone.

The St. Peter Sandstone is a widespread, porous, and permeable quartz sandstone that is generally fine-grained with good lateral continuity. Seals above the St. Peter include several hundred feet of dense limestone and dolostone overlain by approximately 45–75 meters (approximately 150–250 feet) of Maquoketa Shale. Lower salinities may limit the storage resource in the northwest portion of the mapped area.

The Knox Supergroup directly underlies the St. Peter Sandstone and consists of several thousand feet of dolostone and minor sandstone. The Knox is an integrated reservoir and seal interval. Much of the Knox is non-porous dolostone, but scattered throughout are porous and fractured zones (some with vuggy to cavernous porosity) that have permeability suitable for CO_2 injection. The Knox may be particularly important as a storage target in parts of the Illinois Basin where the Mt. Simon Sandstone is too deep or is absent. A multi-state characterization study of the Knox Supergroup and St. Peter Sandstone in the Illinois and Michigan Basins is in progress.

The Mt. Simon Sandstone is commonly used for natural gas storage in the northern Illinois Basin. Although water in the upper Mt. Simon is potable in northernmost Illinois, the formation is saline-filled in the remainder of the state, and no oil or natural gas resources have been discovered in this unit. The Mt. Simon has fair to good permeability and porosity, and the overlying strata contain impermeable limestone, dolomite, and shale intervals. The depth of the Mt. Simon ranges from approximately 610 to 4,265 meters (approximately 2,000 to 14,000 feet) below the surface. At its greatest thickness in the Illinois Basin, the Mt. Simon is more than 790 meters (2,600 feet) thick. The Mt. Simon does not outcrop in Illinois, but correlative units are exposed in southern Wisconsin, southeastern Minnesota, and Missouri. The Mt. Simon exists in the subsurface throughout much of Indiana, Iowa, Michigan, and Ohio. In the southern region of the basin, the potential CO_2 reservoir facies are either too deep or are absent due to post-depositional erosion, especially towards the southwest.

For the current study, Mt. Simon and St. Peter reservoir extents were refined in the southern part of the basin based on well log analysis and regional mapping efforts. The total saline reservoir storage resource for the Illinois Basin is estimated to be 12 billion–158 billion metric tons (13 billion–174 billion tons).

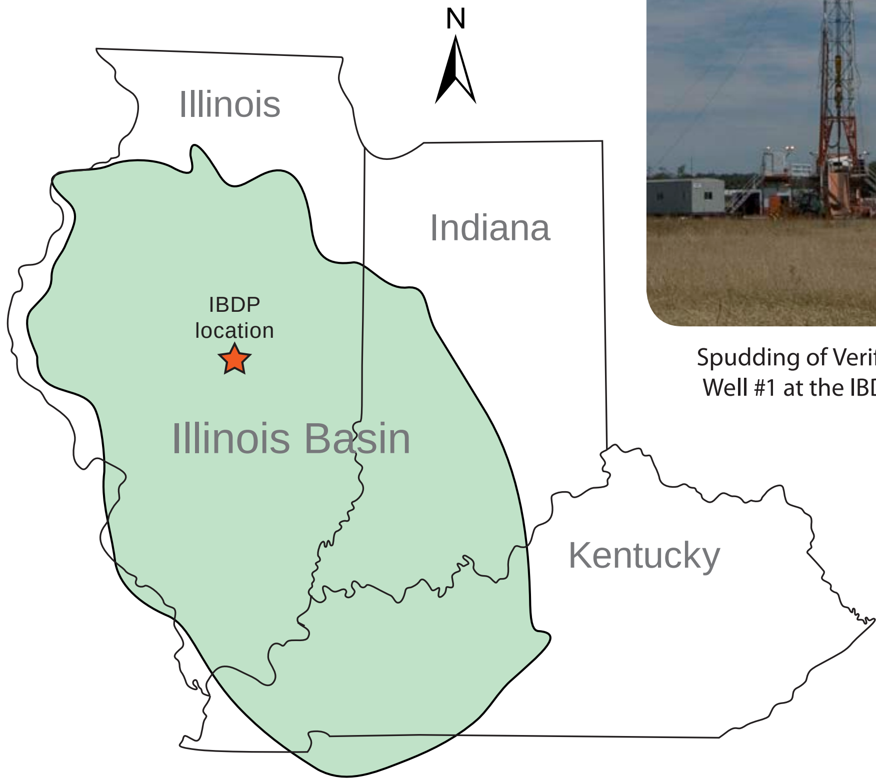
MGSC Large-Scale Demonstration Project

MGSC's Illinois Basin–Decatur Project (IBDP) is a large-scale CCUS demonstration project that is injecting 1 million metric tons (1.1 million tons) of CO_2 over 3 years at a rate of 1,000 metric tons (1,102 tons) per day. The goal of this large-scale project is to demonstrate the potential of the Mt. Simon Sandstone, a major regional saline-water-bearing reservoir to be a significant geologic CO_2 storage reservoir for the Illinois Basin region in the United States.

CO_2 is captured from the ethanol fermentation process at Archer Daniels Midland Company's corn processing complex in Decatur, Illinois. A dedicated compression and dehydration facility built for this project removes water from the CO_2 stream and then compresses the dry CO_2 to a liquid-like dense phase. The compressed CO_2 then travels through a pipeline 1.6 kilometers (1 mile) long to the wellhead where it is injected into a deep saline formation more than 1 mile underground. Up to 1 million metric tons (1.1 million tons) of CO_2 will be injected into the Mt. Simon Sandstone at a depth of approximately 2 kilometers (7,000 feet) over a 3 year period. The Mt. Simon Sandstone is the thickest and most widespread saline reservoir in the Illinois Basin, with an estimated CO_2 storage resource of approximately 11 billion–150 billion metric tons (12 billion–165 billion tons).

Environmental monitoring began in 2008 and continues throughout the project. Tasks include tracking the CO_2 in the subsurface; monitoring the performance of the reservoir seal; and continuous checking of soil, air, and groundwater both during and after injection. The project is permitted under requirements of both the Illinois Environmental Protection Agency and the U.S. Environmental Protection Agency. An injection well drilled in 2009 confirmed site suitability; a 3-D seismic survey, a geophysical monitoring well, and a pressure and fluid sampling (verification) well followed in 2010. Perforation and completion of the verification well and two rounds of fluid sampling were completed by September 2011. Additionally, a 1,100 metric ton (1,210 ton) per day compression/dehydration facility and delivery pipeline was developed to deliver dense phase CO_2 to the wellhead. Operational injection of CO_2 began in November 2011 and will continue through late 2014.

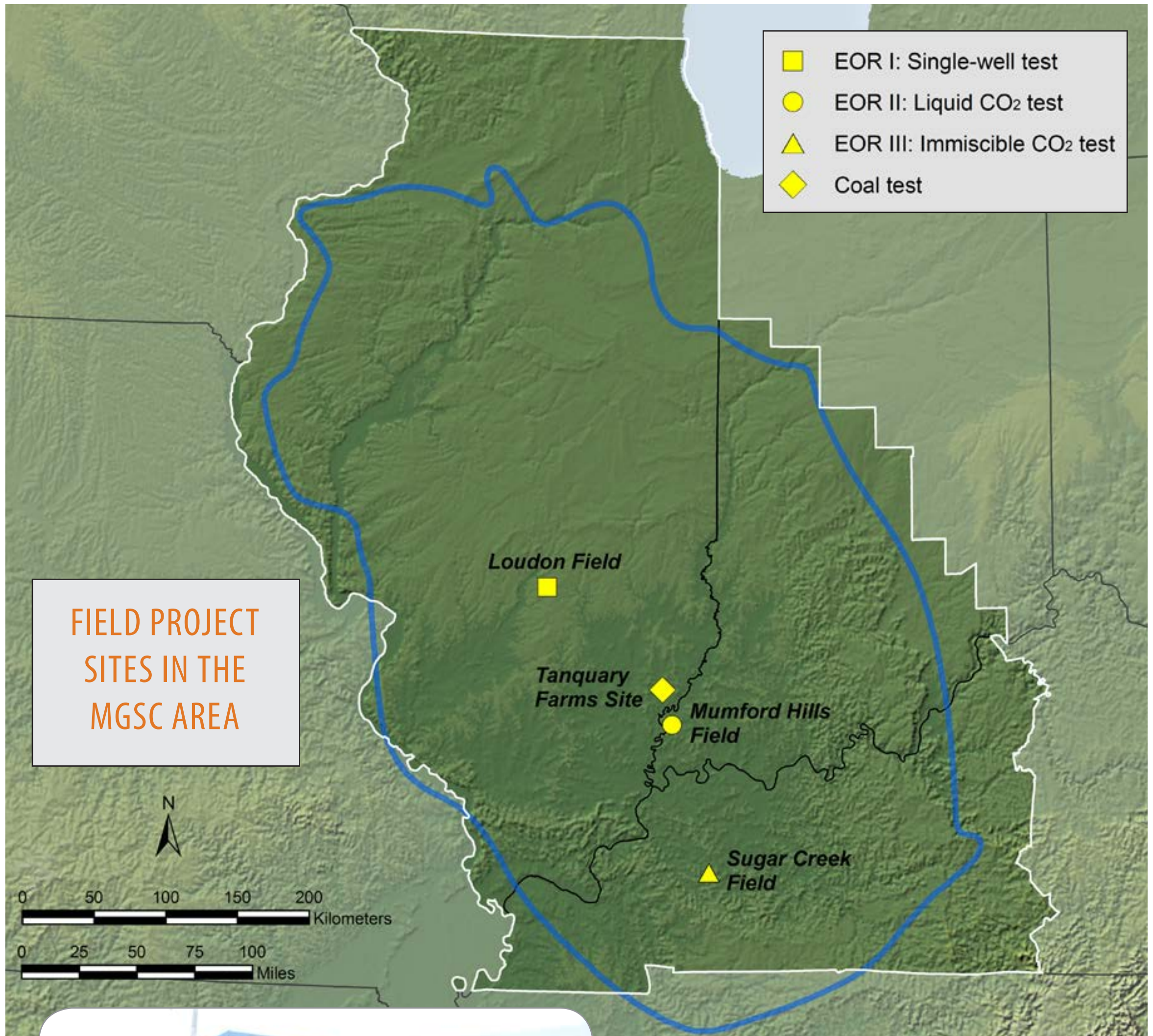
Logging of IBDP injection well concurrent with CO_2 injection.



Spudding of Verification Well #1 at the IBDP site.

First CO_2 to the reservoir at the IBDP site, Nov 17, 2011.

Inside of the IBDP CO_2 compression-dehydration facility.



At left, Injection pump skid with CO_2 supply tanker in the background, Mumford Hills field EOR II site, Indiana.

CO_2 injection at the Tanquary Farms coal test site, Illinois.

Reservoir monitoring well at the Sugar Creek field EOR III site, Kentucky.

MGSC Small-Scale Geologic Pilot Tests Results

MGSC, along with its industry partners, has completed a series of four field validation tests in the Illinois Basin to assess the potential for CO_2 storage in oil reservoirs and coal seams.

Reservoir modeling, computational simulations, and statistical methods were used to assess and interpret field-test data. Monitoring, verification, and accounting (MVA) programs were established to track injected CO_2 and ensure public safety.

MGSC's first small-scale pilot project was an EOR single-well CO_2 huff 'n' puff. The target reservoir was located in the Mississippian Cypress Sandstone at a depth of 457 meters (1,500 feet) at Loudon field in Fayette County, Illinois. The well produced 0.079–0.16 m^3 (0.5–1.0 barrels) of oil per day before injection. About 39 metric tons (43 tons) of CO_2 were injected into the annulus of the oil-producing well over a period of approximately 1 week at a rate of 4.5–9.1 metric tons per day (5–10 tons per day). After injection, the well was shut-in for 1 week and then liquid was produced via a conventional, oilfield rod pump. Over 2 months, the well produced approximately 16 cubic meters (100 barrels) of oil above the pre-injection forecast for oil production.

A miscible (liquid) CO_2 flood pilot project tested CO_2 storage in the Clore Sandstone (Mississippian System, Chesterian Series) at the Bald Unit within the Mumford Hills field in Posey County, southwestern Indiana. A total of 6,300 metric tons (6,950 tons) of CO_2 were injected into the reservoir at rates that ranged from 18 to 32 metric tons per day (20 to 35 tons per day). Approximately 99.5 percent of the injected CO_2 remained in the formation at the Bald Unit after 9 months of post-CO_2 injection monitoring. Reservoir modeling indicated that full-field miscible CO_2 injection for 20 years could result in up to 12 percent incremental oil recovery.

An immiscible CO_2 flood pilot was conducted in the Jackson Sandstone (Mississippian System, Big Clifty Sandstone Member) at the Sugar Creek field in Hopkins County, western Kentucky. A total of 6,560 metric tons (7,230 tons) of CO_2 were injected into the reservoir at rates that ranged from 18.2 to 27.3 metric tons per day (20 to 30 tons per day). After 1 year of post-CO_2 injection monitoring, approximately 16 percent of the injected CO_2 was recovered with produced oil and 84 percent remained in the Jackson sandstone. If there had been a system in place to capture and re-inject the CO_2 back into the injection well, the stored CO_2 would have approached 100%. Model-based projections indicate that full-field immiscible CO_2 injection for 20 years could result in up to 5.5 percent incremental oil recovery.

MGSC tested CO_2 storage in the Middle Pennsylvanian Springfield Coal at the Tanquary Farms site in Wabash County, southeastern Illinois. Approximately 92 metric tons (101 tons) of CO_2 were injected over the duration of the project, at an average rate of 0.93 metric tons per day (1.02 tons per day). Based on model results, the plume was estimated to extend 152 meters (500 feet) in the face cleat direction and 54.9 meters (180 feet) in the butt cleat direction. Using a model calibrated with field data, additional injection scenarios could yield methane recovery of up to 70 percent of the estimated gas-in-place.

The project results showed enhanced oil and gas production, which validated MGSC characterization assessment results and further demonstrated that CO_2 storage in oil reservoirs and coalbeds offers potential increases in hydrocarbon recovery (subject to project economics and scale of deployment). MVA results at each site indicated that the injected CO_2 did not leave the injection zone and that CO_2 injection did not adversely affect groundwater.

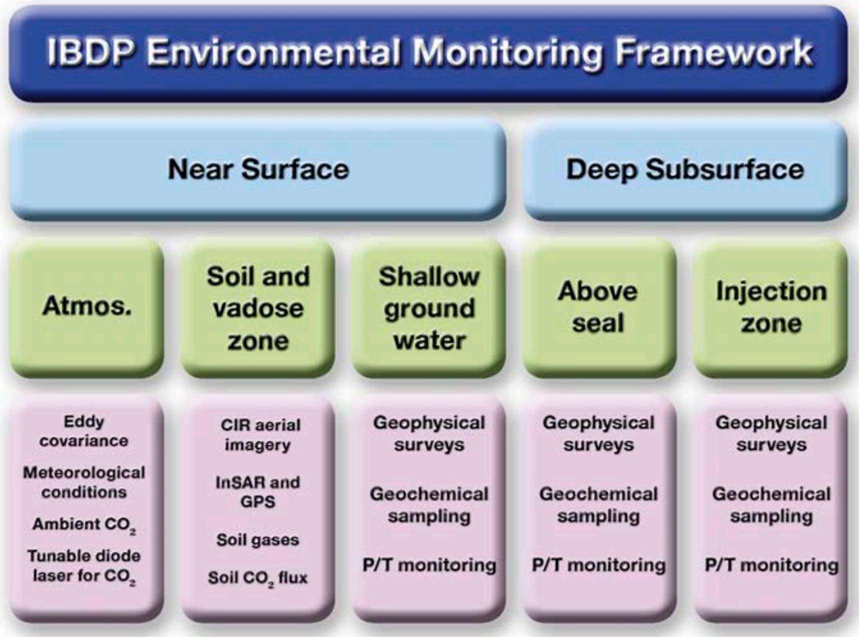
MGSC Monitoring, Verification, and Accounting Protocols

The MGSC large-scale Illinois Basin–Decatur Project (IBDP) MVA Program is a coordinated effort between multiple organizations including the Illinois State Geological Survey, Schlumberger Carbon Services, Archer Daniels Midland, Lawrence Berkley National Laboratory, the University of Illinois, TRE-Canada and the Carbon Capture Project, Physical Sciences Incorporated, and the Illinois Department of Transportation. The program involves environmental measurements, monitoring, and computer modeling throughout the life of the project, and is focused on the 0.65 square kilometer (0.25 square mile) IBDP site. MVA goals include establishing baseline conditions to evaluate the effects of CO_2 injection, demonstrating that project activities are protective of human health and the environment, and providing an accurate accounting of stored CO_2. Researchers are also using the IBDP site to develop and field test carbon storage-related MVA instrumentation and technology.

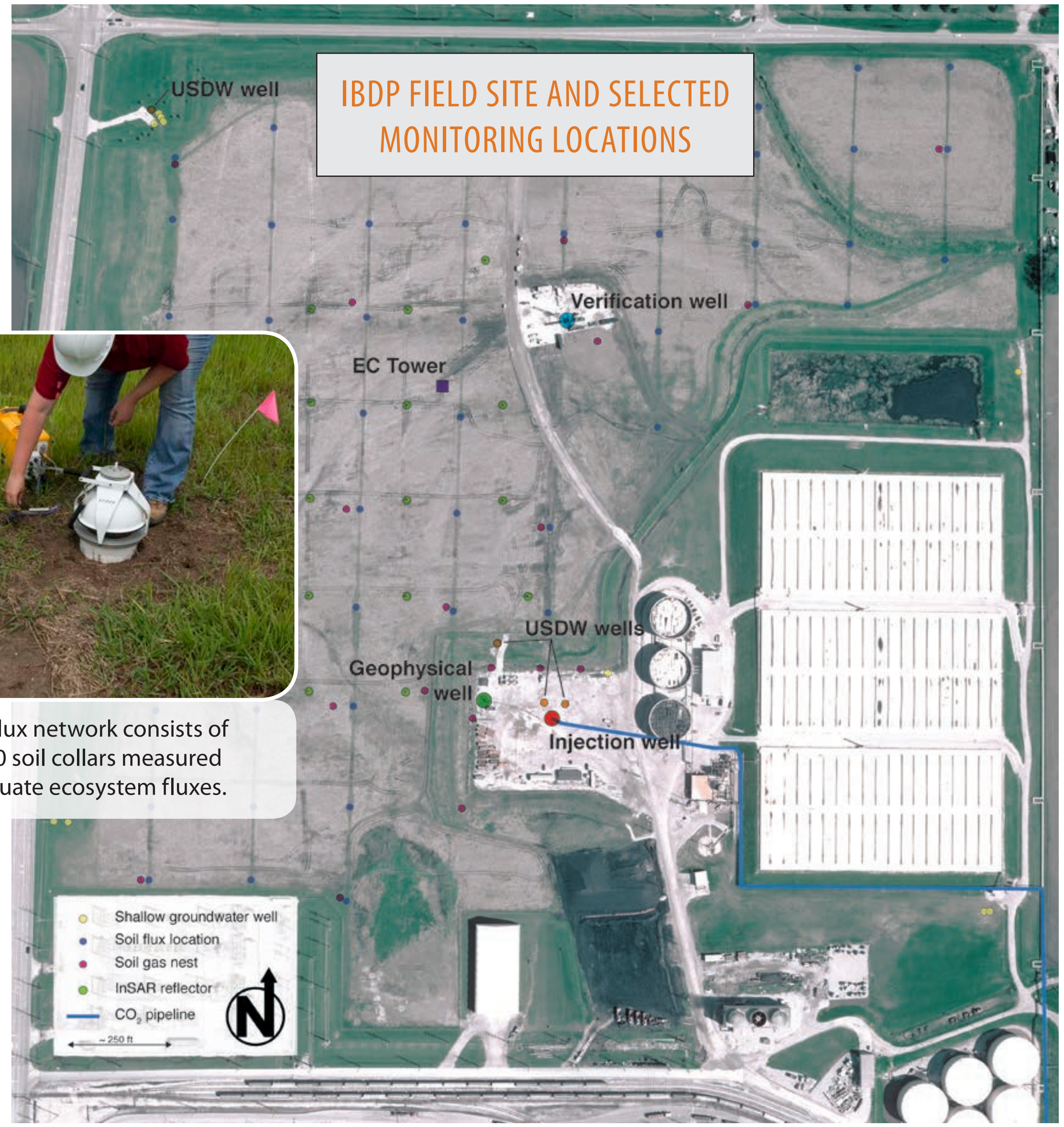
Baseline data have been and continue to be collected from multiple monitoring networks in the atmospheric, near-surface, and deep subsurface regions to detect and monitor CO_2. Near-surface MVA data collection was initiated in 2008 to characterize existing site conditions and study the natural variability of selected environmental parameters. All networks will continue to be monitored during the 3-year injection, as well as the 3-year post-injection period.

For atmospheric monitoring, meteorological data are collected and an eddy covariance station is in operation to measure the net flux of CO_2. Near-surface monitoring includes soil gas and soil CO_2 flux monitoring, shallow groundwater sampling, high-resolution earth electrical resistivity surveying, satellite-borne radar measurement of ground surface deflection by InSAR techniques, and color-near infrared aerial imagery to assess vegetative health and vigor.

Deep subsurface monitoring and characterization techniques include passive microseismic monitoring, periodic borehole logging of the injection and reservoir monitoring well, 2-D and 3-D geophysical surveys, pressure and temperature monitoring, and fluid sampling from discrete zones within and above the injection reservoir using a Westbay* multilevel groundwater characterization and monitoring system. In particular, geophysical techniques, such as vertical seismic profiles, will allow researchers to track the movement of CO_2 within the saline formation.



Fluid sampler being retrieved from the IBDP verification well.



The IBDP soil flux network consists of more than 100 soil collars measured weekly to evaluate ecosystem fluxes.

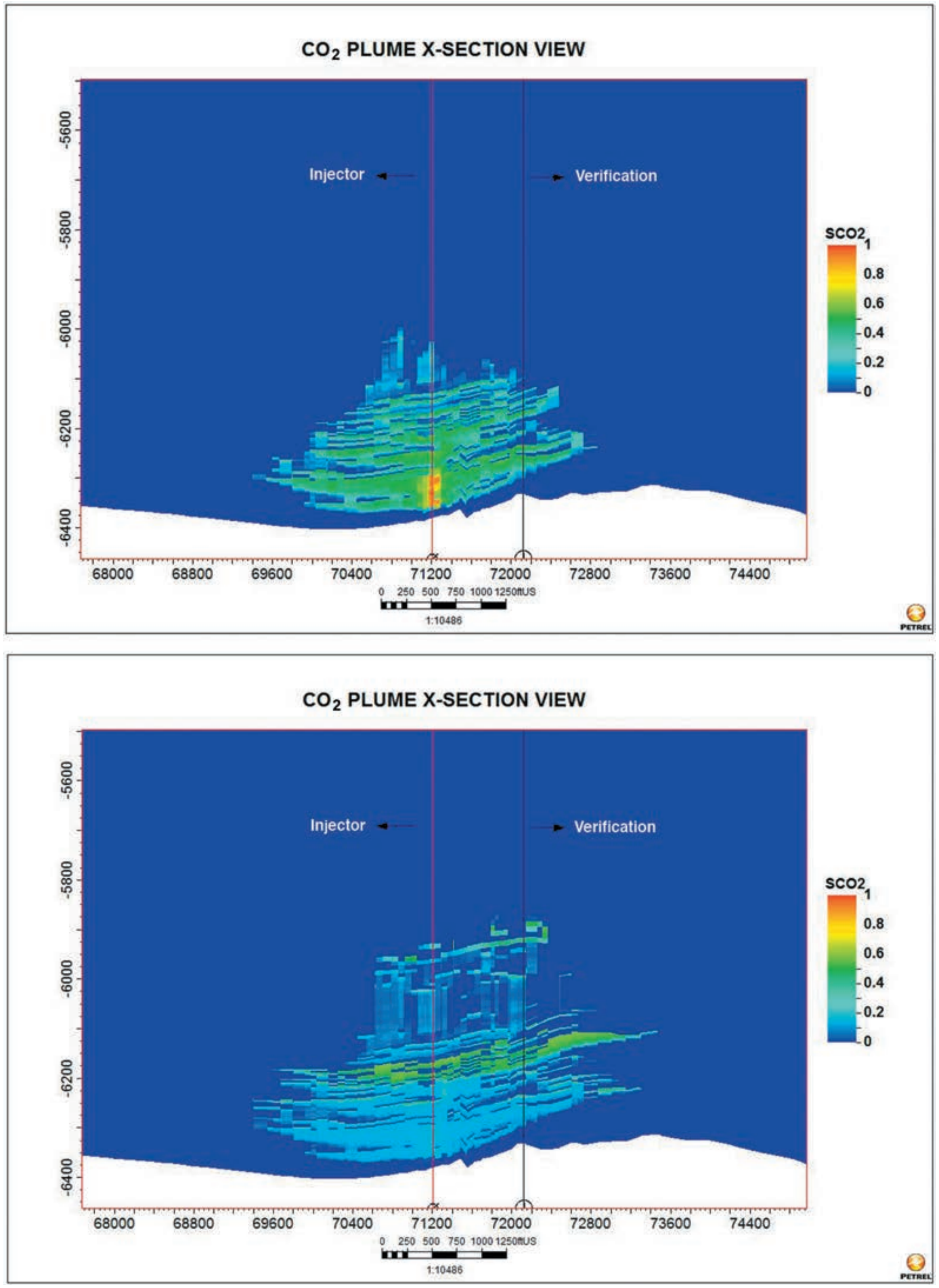
* Mark of Schlumberger

MGSC Modeling Activities

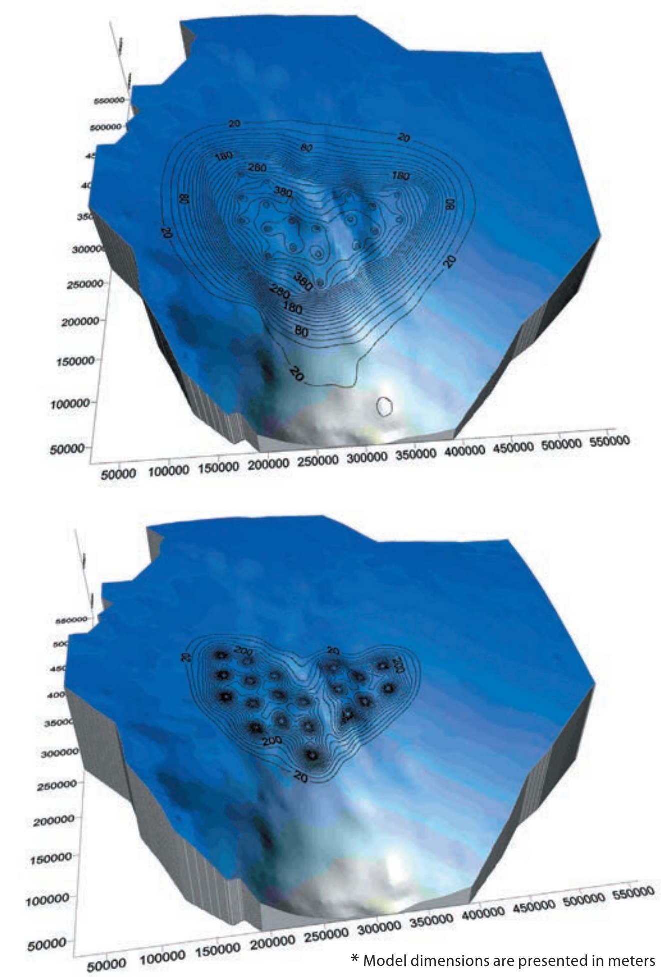
Numerical modeling of geologic carbon storage is being conducted to analyze, understand, and enhance MGSC field testing at the Illinois Basin–Decatur Project (IBDP) site. For this work, CO_2 injection into the Mt. Simon Sandstone is simulated at the well scale, local scale, and regional scale. Simulation studies for the Illinois Basin–Decatur Project started in 2008 using general, regional knowledge. Over time, the models have increased in complexity and now better represent the Mt. Simon Sandstone as more site-specific data have been acquired and incorporated.

At the well scale, predictive reservoir simulations are underway to help interpret the petrophysical, geochemical, and 3-D seismic data collected at the IBDP site. The main goal of reservoir modeling is to predict the geometry of the CO_2 plume in the deep subsurface during and after injection, and identify possible CO_2 migration pathways within the injection reservoir. Predictions of the CO_2 saturation profile and possible migration pathways play an important role in risk analysis and mitigation planning. Once analyzed, uncertainty in the modeled CO_2 saturation and pressure profiles within the reservoir may reveal potential implications for regulatory requirements involving Area of Review evolution during the life of the project. Important characteristics of the storage site, such as CO_2 capacity, injectivity, and containment, are often evaluated based on the results of reservoir modeling.

Researchers have applied basin-scale numerical modeling to predict the regional subsurface pressure effects of potential geologic carbon storage activities on the injection reservoir. The regional model assumes that 100 million metric tons (110 million tons) of CO_2 is injected annually for 50 years into the Mt. Simon Sandstone from 20 wells located throughout the central Illinois Basin. Site-specific geologic data, such as porosity, permeability, facies, and reservoir layering, from the IBDP CCUS #1 injection well are integrated with other regional geologic data sets and then collectively input into the Illinois Basin CO_2 injection model. A key goal of the basin-scale study is to understand the role of the geologic properties of the Mt. Simon Sandstone reservoir and the Eau Claire Formation (primary seal) on the pressure response and CO_2 distribution in a multi-well CO_2 injection scenario. This work used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant number OCI-1053575.



Simulated CO_2 plume in the lower Mt. Simon Sandstone at the IBDP site, showing: (top image) distribution and saturation of CO_2 following the completion of three years of continued CO_2 injection, and (bottom) 50 years after initial injection showing effects of dissolution and reservoir layering.



Contours of predicted pressure increase (in psi) at the top of the Mt. Simon Sandstone, due to a hypothetical 50 years of regional CCUS activities within the Illinois Basin. Geologic model 1 *(at top)* was developed with data available prior to drilling the CCUS#1 CO_2 injection well at the IBDP site. Geologic model 2 *(at bottom)* was based on geologic data obtained solely from the CCUS#1 well. Model 1 predicts that the Mt. Simon can accept 100 million metric tons of CO_2 per year, whereas improved data in Model 2 predict the reservoir may only accept 50 million metric tons of CO_2 per year, due to lower injection zone permeability.

Commercialization in the MGSC Region

The states within the Illinois Basin region are actively considering initiatives that would facilitate deployment of geologic CO_2 storage. Organizations within the region are promoting advanced coal technology research and commercialization studies.

Joint commercial opportunities for CO_2 storage and coal-fired electricity generation continue to be researched in Illinois, including projects like FutureGen 2.0 (coal oxy-combustion) in Morgan County and the Taylorville Energy Center (coal gasification) in Christian County. The Illinois Industrial Carbon Capture and Storage project will expand current CCUS operations at an ethanol plant in Decatur, Illinois. MGSC and partners continue to engage in CO_2 storage research and supply information to interested commercial parties. A pipeline to carry Illinois Basin CO_2 south for EOR has been considered but is dependent on development of multiple source projects, which have not yet been finalized.

In 2007, the Kentucky State Legislature funded a broad program of carbon storage and enhanced oil recovery/enhanced gas recovery projects to demonstrate the potential for storage in the Commonwealth. The Kentucky Consortium for Carbon Storage was formed by the Kentucky Geological Survey to conduct the tests. A second phase of CO_2 injection testing in the Knox Supergroup in the Kentucky Geological Survey Blan #1 well in Hancock County, Kentucky, was completed in September 2010. This work followed initial CO_2 injection testing in August 2009. Phase II injection testing focused on a more limited zone—the Gunter Sandstone—that possess the highest porosity and permeability within the Knox Supergroup. A total of 332 metric tons (367 tons) of CO_2 was injected at a rate of 0.40 metric tons (0.44 tons) per minute.

The Kentucky Geological Survey has completed a project to evaluate CO_2 storage potential at five coal-fired power plants in central and western Kentucky. The Kentucky Energy and Environment Cabinet funded this work to provide necessary data for proposing an integrated CCUS demonstration project.

Two proposed coal to synthetic natural gas projects in western Kentucky have been delayed, presumably due to low natural gas prices. Neither the Cash Creek (integrated gasification combined cycle, Henderson County) nor the Kentucky NewGas (Muhlenberg County) projects have begun construction as of early 2012. Low natural gas prices are shifting the focus of new coal gasification projects to hydrocarbon liquids production. A new coal to gasoline gasification plant has been proposed in McCracken County, Kentucky, and is currently in the permit-approval stage. Plans for any capture and/or storage of CO_2 produced by this project have not been announced.

Aerial image of ADM plant, Decatur, Illinois.

CO_2 injection testing in the Blan #1 well, Hancock County, Kentucky.

CO_2 storage tanks (Phase 2 injection) on the well site at the KGS' Marvin Blan #1 well, Hancock County, Kentucky.

Midwest Regional Carbon Sequestration Partnership

The Midwest Regional Carbon Sequestration Partnership (MRCSP) region consists of nine neighboring states: Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and West Virginia. Battelle Memorial Institute leads MRCSP, which includes nearly 40 organizations from the research community, energy industry, universities, non-government, and government organizations. The region has a diverse range of CO_2 sources and many opportunities for reducing CO_2 emissions through geologic storage and/or EOR.

Potential locations for geologic storage in the MRCSP states extend from the deep rock formations in the broad sedimentary basins and arches in the western portion of the region to the offshore continental shelf along the East Coast. MRCSP research and testing has established many promising geologic units for CO_2 storage, including deep saline rock formations, depleted oil and gas reservoirs, organic shale layers, and coalbeds. Gaining a better understanding of the distribution of these formations across nine states and their CO_2 storage resource is a focus of MRCSP's continuing geologic research. Currently, MRCSP is moving forward on a developmental-scale project in Otsego County, Michigan, aimed at a 1 million metric ton (1.1 million ton) CO_2 injection into a Niagaran reef rock interval. Reports, data, and maps generated by MRCSP research are available on the MRCSP website, www.mrcsp.org.

Contact

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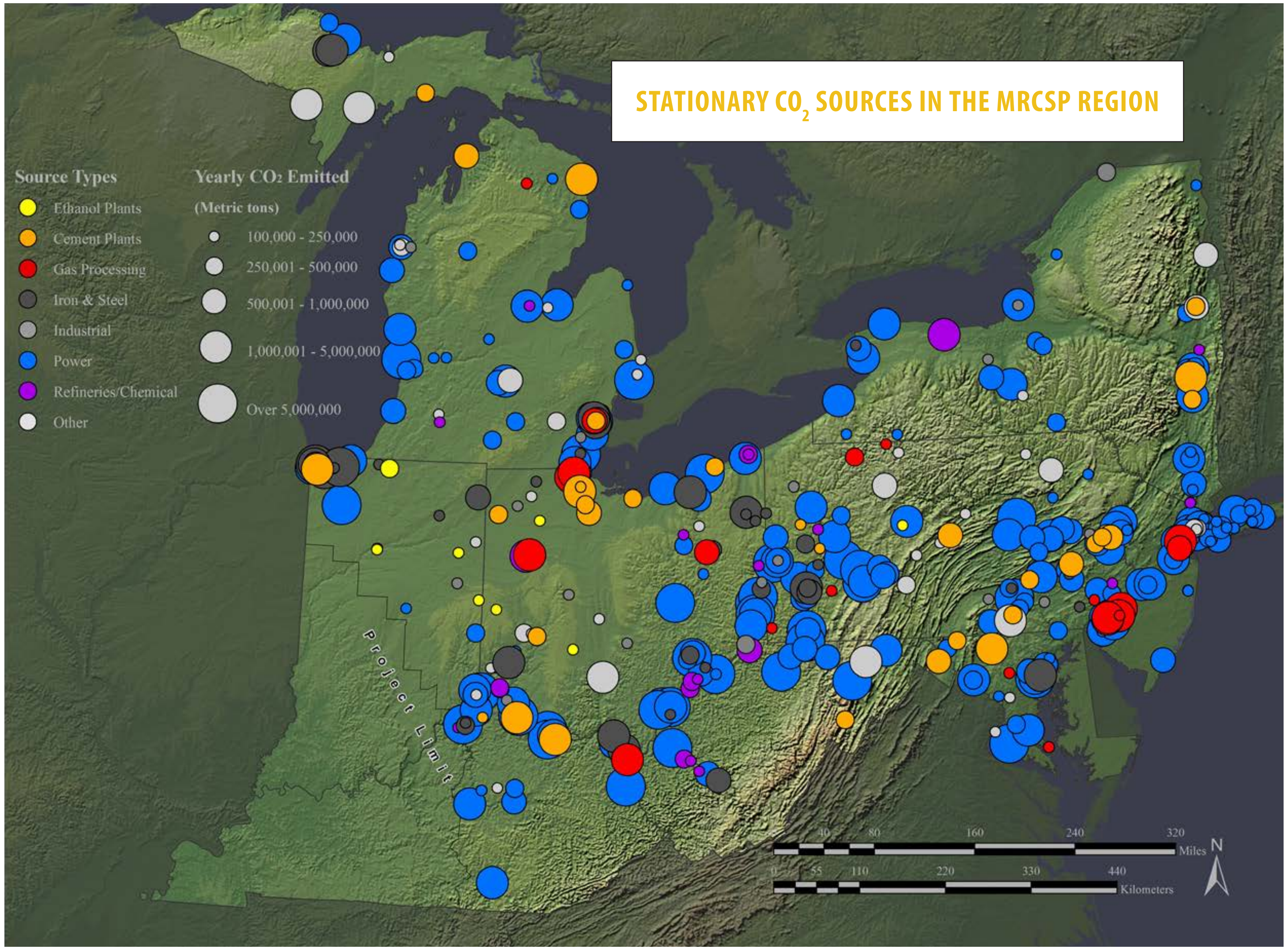
MRCSP CO_2 Sources

A Snapshot of the MRCSP Region

- Nine states—Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and West Virginia
- Population—80.4 million (26 percent of U.S. population)
- Gross regional product—$3,114 billion (27 percent of U.S. economy)
- 30 percent of all electricity generated in the United States
- 80 percent of the CO_2 emissions are related to power generation

CO_2 Sources in the MRCSP Region

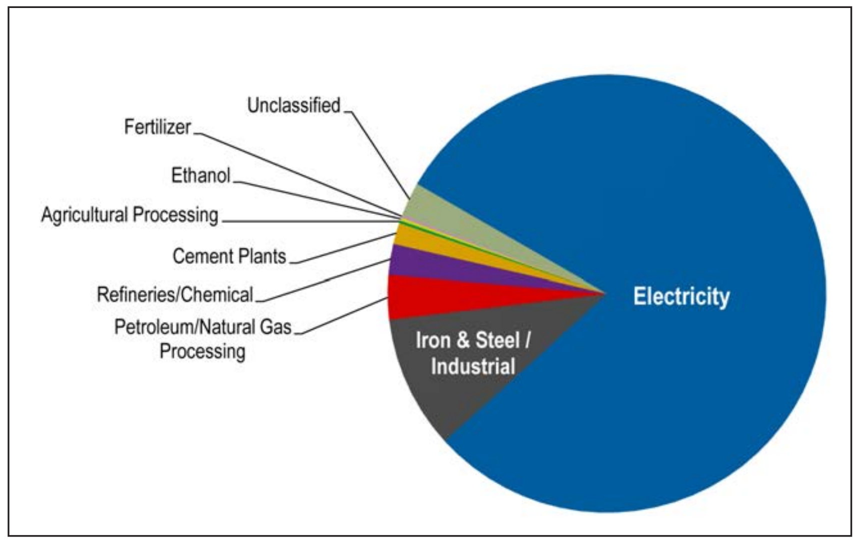
Due to its large and diverse economy, the MRCSP region includes a large variety of greenhouse gas sources. While distributed sources, such as agriculture, transportation, and home heating, account for a large portion of CO_2 emissions in the MRCSP region, more than half of CO_2 emissions are linked to stationary sources. In total, approximately 670 million metric tons (740 million tons) of CO_2 are emitted each year from these stationary sources. Emissions are highest along the Ohio River Valley and coastlines, where many power plants and industries are located. Electricity generation in the MRCSP region accounts for approximately 80 percent of the region's CO_2 stationary source emissions.



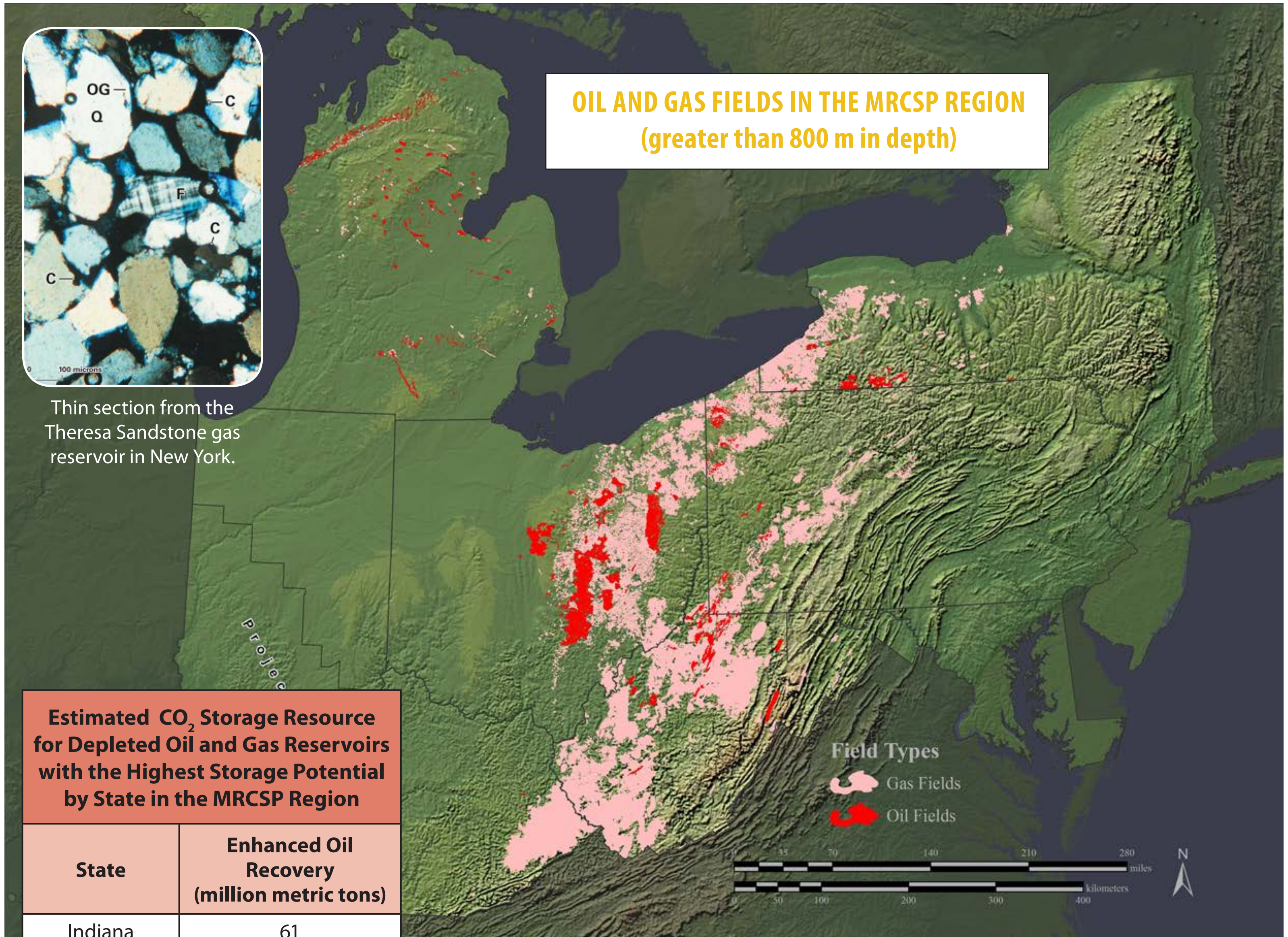
Stationary CO_2 Source Emissions in the MRCSP Region*			
Category	**Million Metric Tons CO_2 per year**	**MRCSP%**	**Count**
Electricity Generation	535	79.9%	233
Iron & Steel/Industrial	66	9.9%	63
Petroleum and Gas Processing	21	3.2%	27
Refineries/Chemical	15	2.3%	41
Cement Plants	10	1.6%	17
Agricultural Processing	1	0.2%	9
Ethanol Plants	1	0.2%	8
Fertilizer	1	0.2%	1
Unclassified	17	2.5%	44
Total	**670**	**100%**	**443**

* Based in 2010 EPA GHG reporting data for individual sources greater than 100,000 metric tons CO_2 per year.

MRCSP has tested CO_2 injection at several existing CO_2 point sources in the region.



Pie chart showing a breakdown of CO_2 source emissions in the MRCSP region.



Thin section from the Theresa Sandstone gas reservoir in New York.

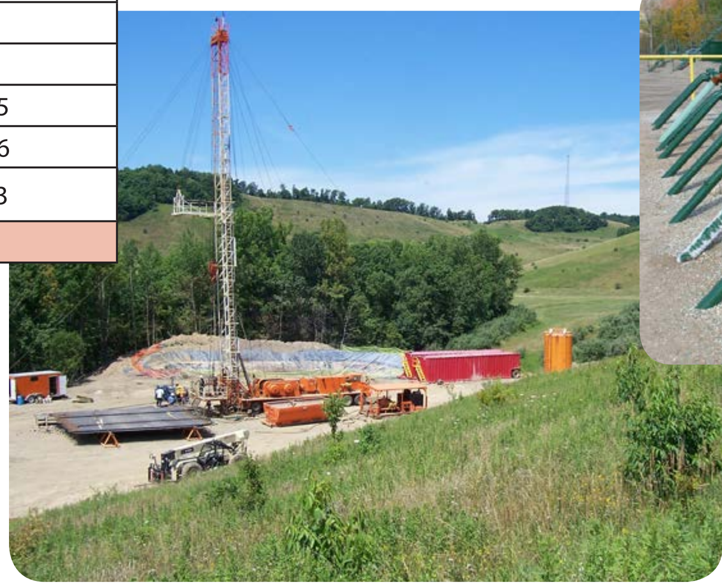
Estimated CO_2 Storage Resource for Depleted Oil and Gas Reservoirs with the Highest Storage Potential by State in the MRCSP Region

State	Enhanced Oil Recovery (million metric tons)
Indiana	61
Kentucky	87
Michigan	457
New York	272
Ohio	3,405
Pennsylvania	2,806
West Virginia	1,423
Total	

MRCSP Oil and Gas Reservoirs

Commercial exploration in the MRCSP region began in 1859 with the discovery of oil in a shallow well drilled by "Colonel" Edwin Drake in Titusville, Pennsylvania. Since then, the MRCSP region has produced more than 5 billion barrels of oil and more than 50 trillion cubic feet of natural gas. In addition, the MRCSP region includes four of the top seven natural-gas storage states in the United States. Such large volumes of gas storage capacity (both natural and engineered) strongly suggest that CO_2 can be successfully managed in subsurface reservoirs within the MRCSP region. There also is potential for value-added production of oil and natural gas associated with CO_2 utilization and storage. The oil and gas fields in the region are most concentrated in the Appalachian and Michigan sedimentary basins. MRCSP research suggests that oil and gas fields have a storage resource of 8,500 million metric tons of CO_2. Much of this resource is intermixed with deep saline formations.

Oil and gas reservoirs cover large portions of the Appalachian Basin with significant fields in eastern Kentucky, Michigan, western New York, Ohio, western Pennsylvania, and West Virginia. Key oil and gas formations in the Appalachian Basin include Devonian Shales, "Clinton"/Medina/Tuscarora Sandstones, the Oriskany Sandstone, and the Rose Run Sandstone. Within the Michigan Basin, oil and natural gas reservoirs are concentrated along the Niagaran reef trend and Devonian Antrim Shales in the northwestern margin of the basin and the southern margin of the basin. Review of reservoir conditions indicates that a large amount of oil and gas remains in place in many of these fields. Thus, opportunity exists for enhanced oil and gas production associated with CO_2 utilization and storage in the MRCSP region.


This gas well in Ohio was also utilized to evaluate CO_2 storage rock units.

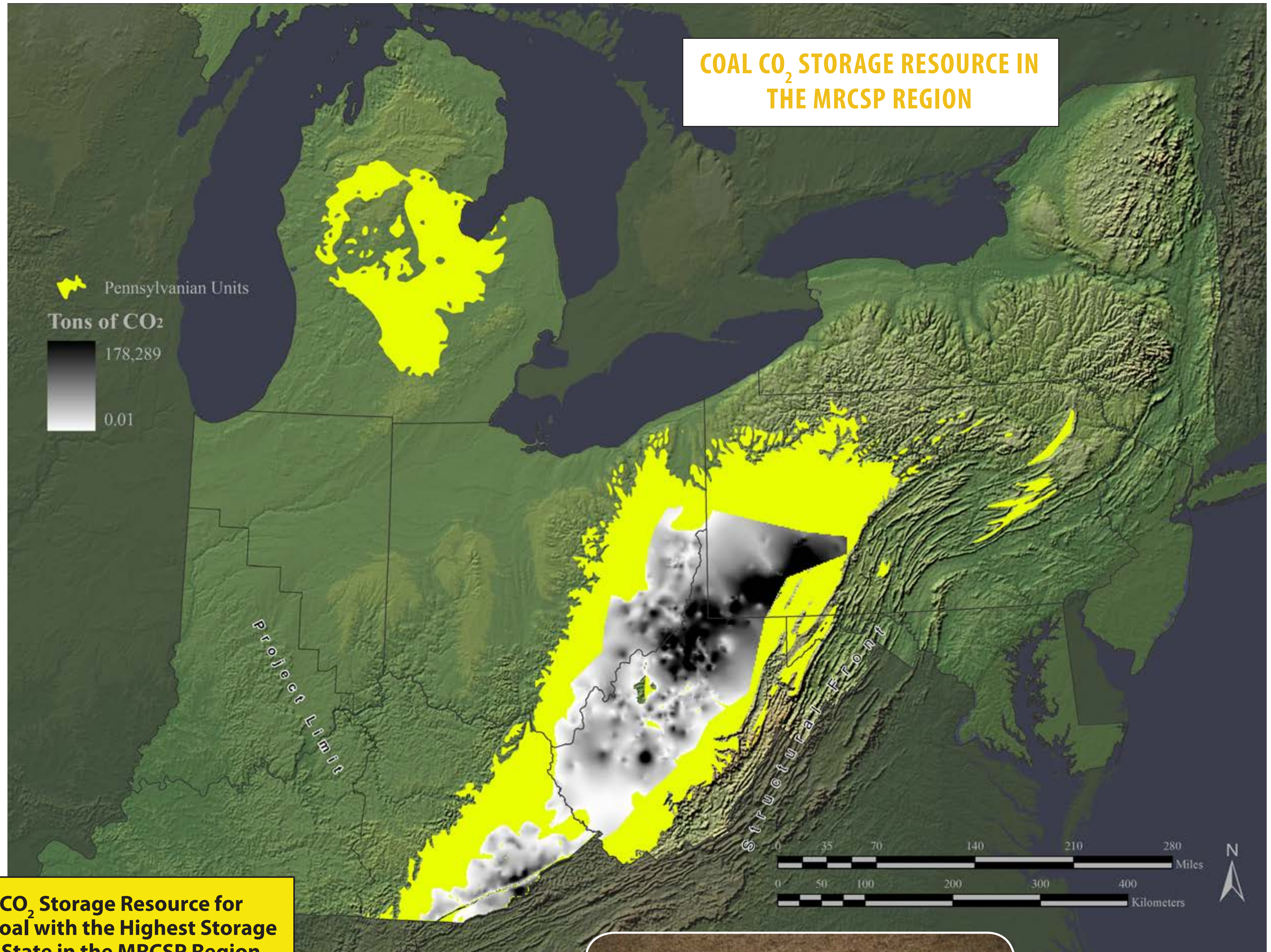

CO_2-EOR operations in Michigan.


The MRCSP region has a long history of oil and gas production.

MRCSP Unmineable Coal

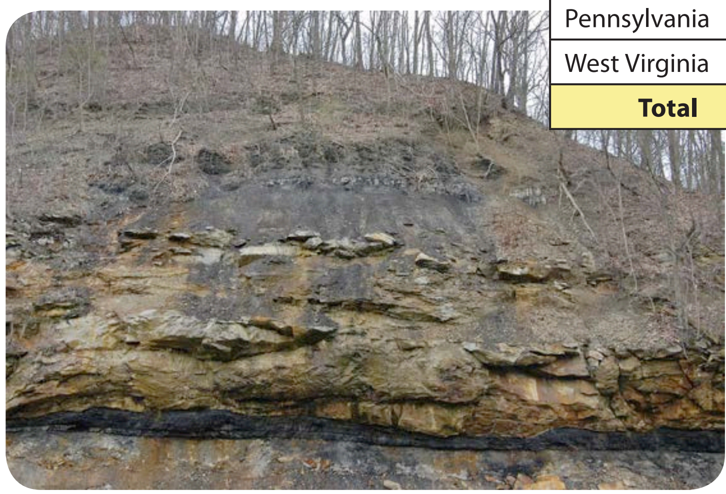
The MRCSP region contains the second- (West Virginia), third- (Kentucky), fourth- (Pennsylvania), and fourteenth- (Ohio) leading coal-producing states in the nation. Bituminous coal seams are located in the Appalachian and Michigan Basins and anthracite coal seams are located in the state of Pennsylvania. Deep unmineable coal seams in the Appalachian Basin with the highest resource for CO_2 storage are located along the Ohio River Valley in Kentucky, Ohio, Pennsylvania, and West Virginia.

There is also potential for using CO_2 for ECBM recovery in the Appalachian Basin. In the last decade, significant coalbed methane production has occurred in some of these historic 'gassy' coals, particularly in southern West Virginia. Coalbed methane is locally produced from at least 24 pools in Pennsylvania, and both historic and modern coalbed methane fields occur in the northern portion of West Virginia. Furthermore, coalbed methane production has been reported in eastern Kentucky and in Ohio, where historic coalbed methane production occurred as early as 1924. Interest in coalbed methane production and exploration is growing in the basin, as is CO_2 storage potential. As part of the MRCSP small-scale efforts, coal samples were tested from a well in Pennsylvania at depths greater than 1,000 feet to better define CO_2 storage potential for the region.



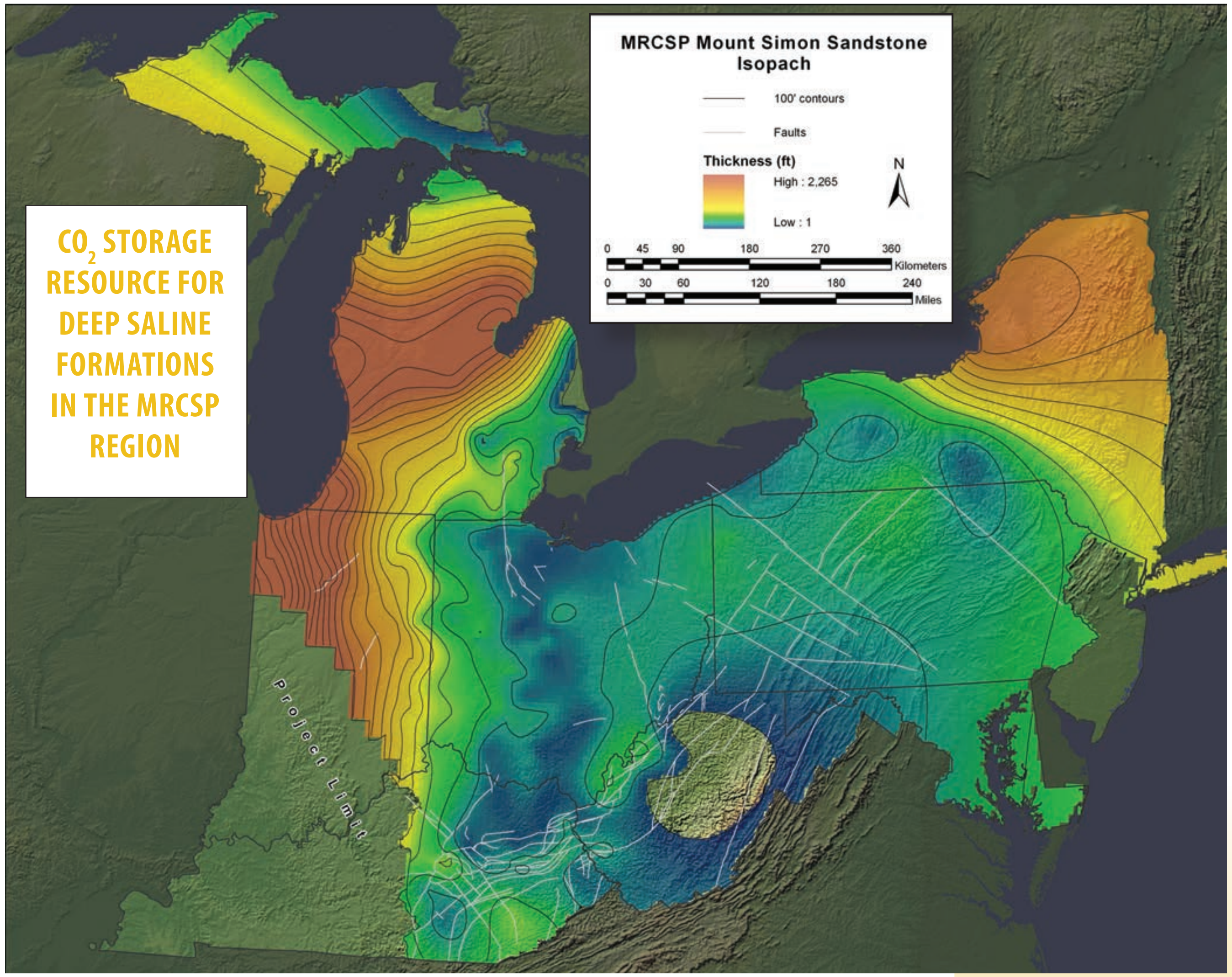
Estimated CO_2 Storage Resource for Unmineable Coal with the Highest Storage Potential by State in the MRCSP Region

State	Million Metric Tons
Kentucky	17
Ohio	31
Pennsylvania	66
West Virginia	92
Total	**206**



Coalbed in Kentucky.

MRCSP researchers sampling deep coal seams in Pennsylvania.



MRCSP Saline Formations

Deep saline formations are the MRCSP region's largest resource for long-term geologic CO_2 storage. The estimated CO_2 storage resource for the region is large enough to accommodate CO_2 emissions from stationary sources for hundreds of years. Research suggests a storage resource of approximately 48,670 million–194,250 million metric tons (53,650 million–214,120 million tons) within onshore, deep saline formations in the MRCSP region. Saline formations in the MRCSP region are widespread, close to many large CO_2 sources, and suitable for storage applications in many areas.

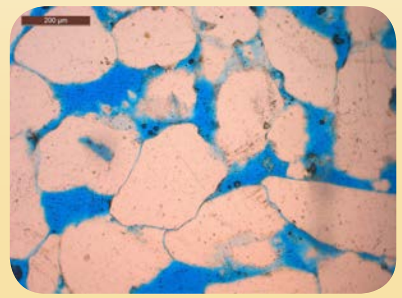
Throughout the western MRCSP states, thick sequences of sedimentary rocks are present in the form of broad basins and arches. In the eastern states, coastal plain deposits along the continental shelf are potential storage zones, as are deep rocks in the eastern basins saturated with dense brine fluids. In addition, the region is considered a fairly stable geologic setting. Distinct rock formations have been correlated and mapped based on rock layers encountered in oil and gas wells.

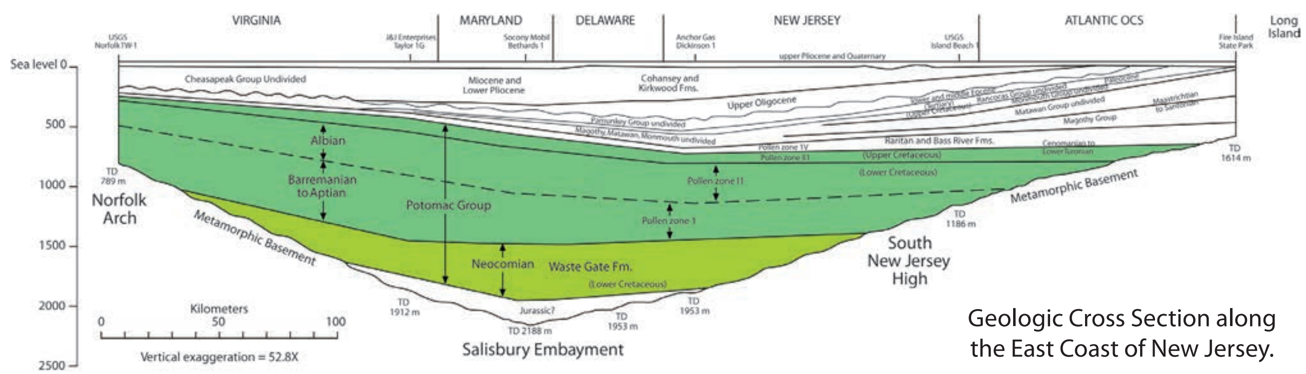
The storage resource in each formation is largely a function of its spatial extent, thickness, and porosity. The deep saline formation with the largest resource in the MRCSP region is the Mt. Simon Sandstone. Other notable storage formations include the St. Peter Sandstone, the Rose Run Sandstone, the Lockport Group, and the Medina/Tuscarora Sandstone. Some areas of the MRCSP region may have additional storage options, such as porosity zones in the Knox Dolomite. Offshore, initial studies indicate areas along the U.S. East Coast may contain a large storage resource, possibly exceeding the onshore resource.

Potential CO_2 Storage Resource (million metric tons)			
Deep Saline Formation	**Low**	**Medium**	**High**
Mt. Simon Sandstone	16,900	42,200	67,600
St. Peter Sandstone	8,800	22,000	35,200
Rose Run Sandstone	6,100	15,300	24,400
Lockport Group	4,500	11,300	18,100
Medina/Tuscarora Sandstone	4,000	10,000	16,000
Onshore New Jersey Potomac Sands	2,950	7,350	11,760
Bass Islands Group	1,560	3,900	6,040
Sylvania Sandstone	1,510	3,800	3,500
Oriskany Sandstone	720	1,800	2,880
Dundee, Waste Gate, Conasauga, Potsdam, Rome Trough Sandstone	1,630	4,080	8,770
(Offshore New Jersey Cretaceous Sands)	(164,500)	(411,400)	(658,200)
Total Deep Saline Formation*	**48,670**	**121,730**	**194,250**

* Note: Offshore New Jersey resource was not included in the total deep saline formation calculation.

MRCSP rock samples collected and tested to assess their CO_2 storage resource potential.



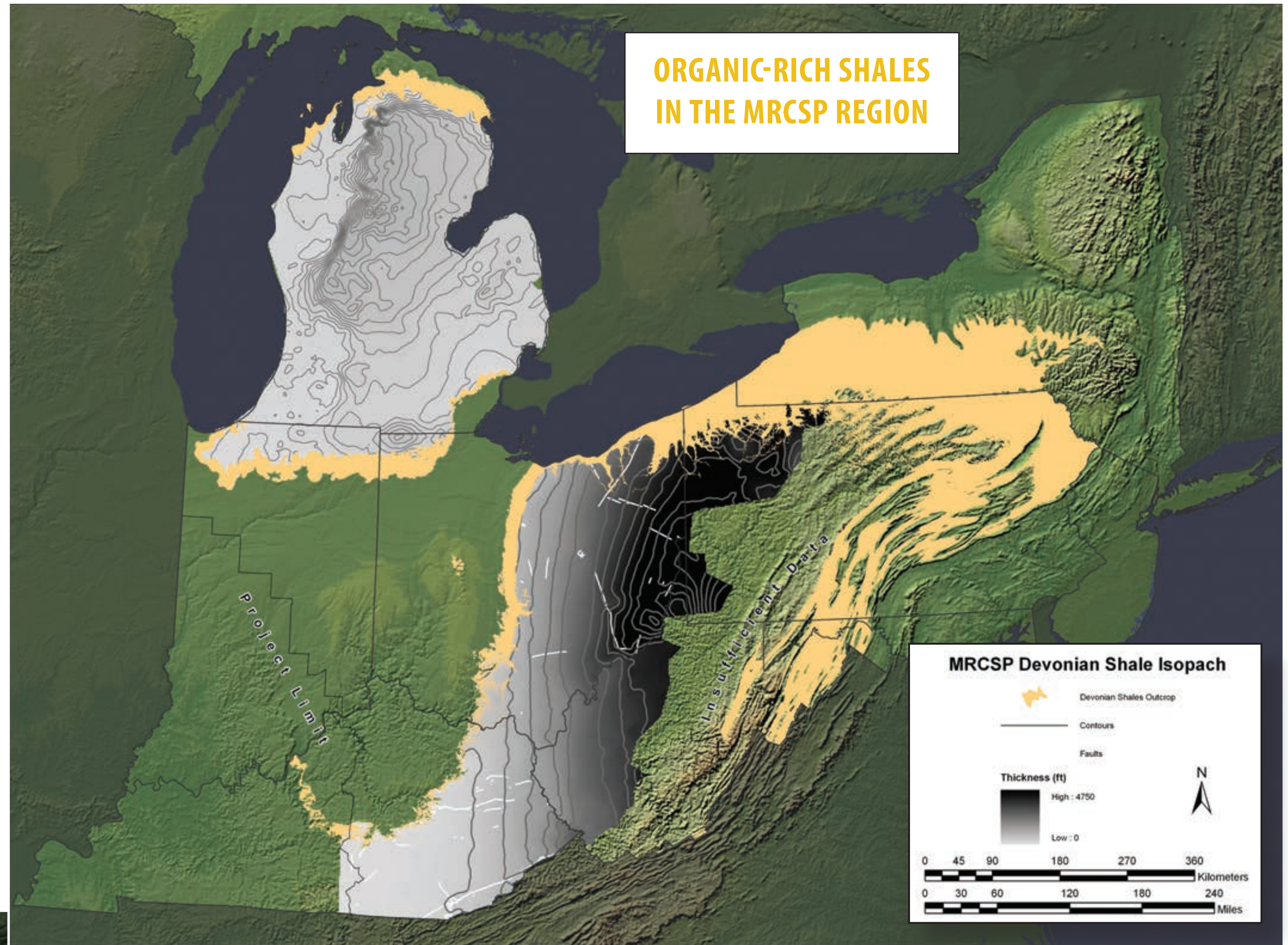


Geologic Cross Section along the East Coast of New Jersey.

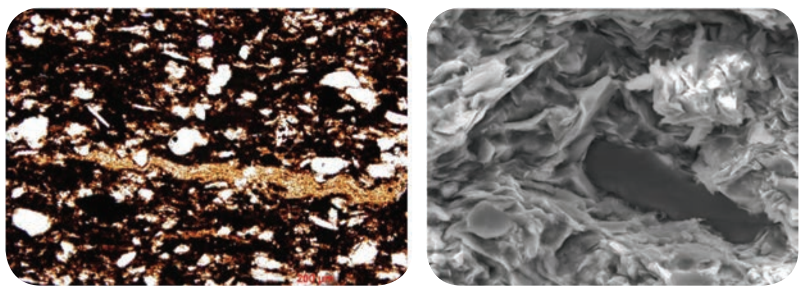
MRCSP Organic-Rich Shale Basins

The MRCSP region contains widespread, thick deposits of organic-rich shales. These shales are often multifunctional—they act as seals for underlying reservoirs, as source rocks for oil and gas reservoirs, and as unconventional gas reservoirs themselves. Analogous to storage in coalbeds, CO_2 injection into unconventional carbonaceous shale reservoirs could be used to enhance existing gas production. As an added feature, it is believed the carbonaceous shales would adsorb the CO_2, permitting long-term CO_2 storage, even at relatively shallow depths.

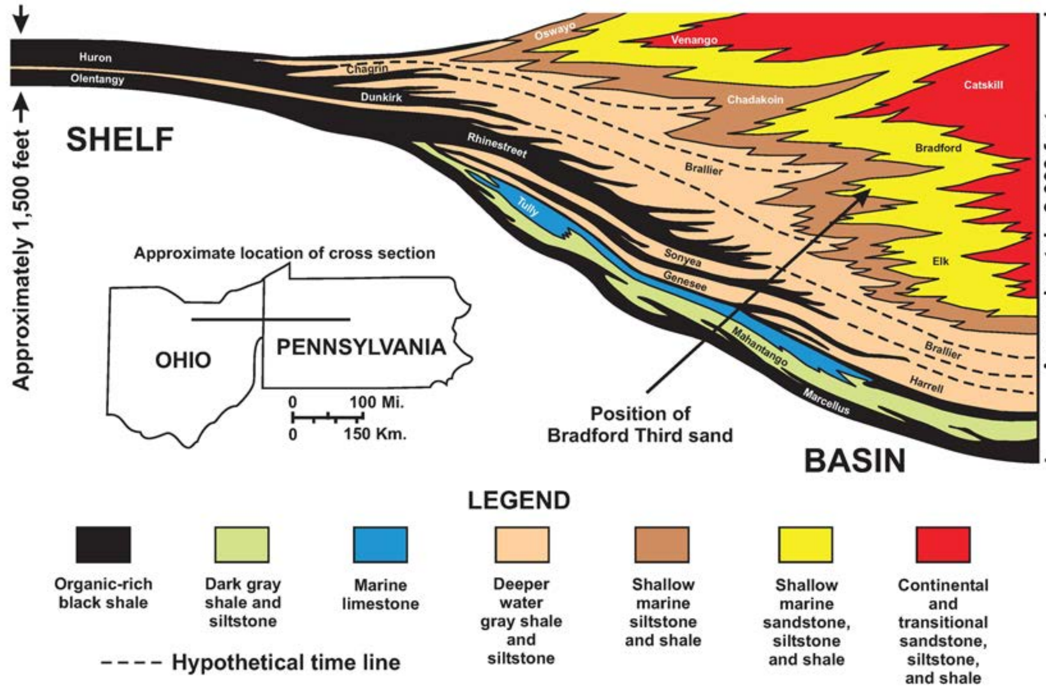
Organic shales are thickest in Kentucky, Ohio, West Virginia, and portions of Pennsylvania. In addition, shales are present throughout the Michigan Basin. Analysis of these rock formations indicates a CO_2 storage resource of approximately 2,230 million– 29,680 million metric tons (2,460 million–32,720 million tons). The Marcellus and Utica Shales are organic-rich shales that have been the focus of increased oil and gas exploration in the MRCSP region. Because the fields are near many large CO_2 sources, these rock formations may have additional potential for combined CO_2 utilization and storage.



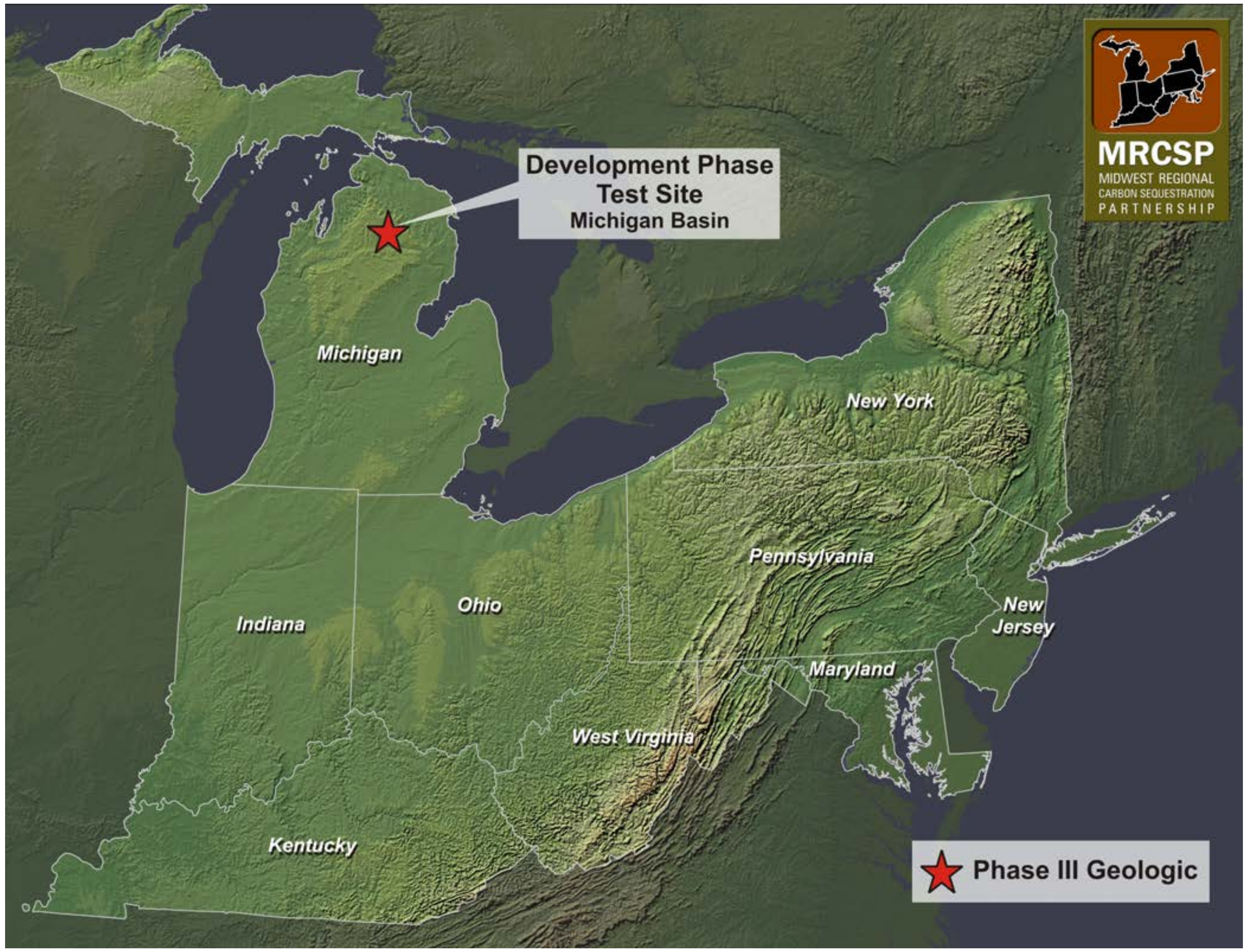
Shale Outcrop in Ohio.



Photomicrograph of shale samples showing organic material.



Geologic Cross Section Showing Shale Layers in Ohio and Pennsylvania.

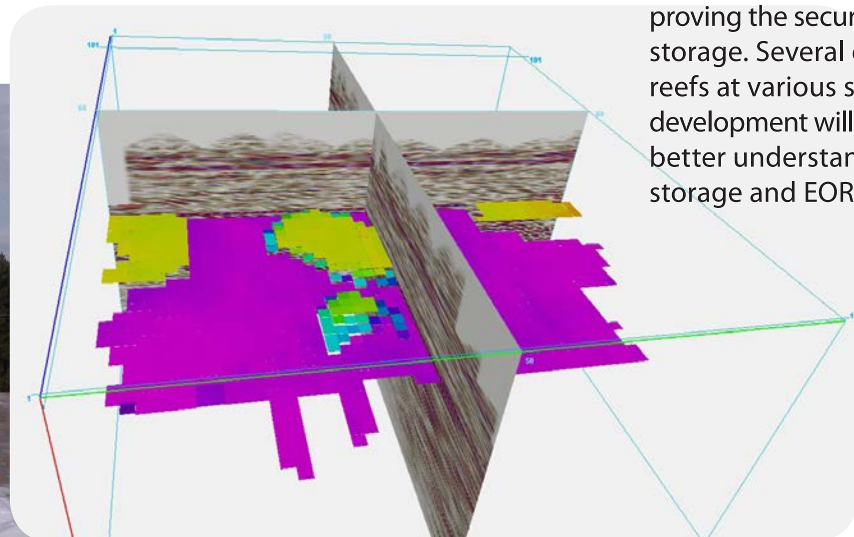


MRCSP Large-Scale Field Project – Overview

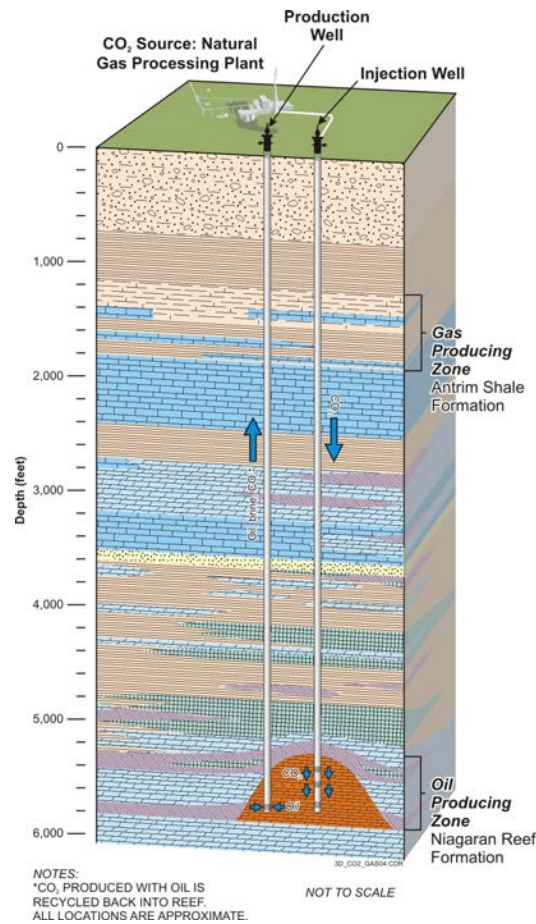
The MRCSP large-scale field project continues to develop carbon storage technology as part of a regional strategy to reduce the amount of CO_2 emitted into the atmosphere. MRCSP's large-scale test site is located in Otsego County, Michigan, near a natural gas processing and compression facility, which is the source of CO_2 for the test. The facility currently produces 640 metric tons per day of high purity CO_2. The CO_2 is a constituent of natural gas produced from Antrim shales in the area. The CO_2 is stripped from the natural gas at a processing facility so the natural gas is suitable for burning. The CO_2 is either vented to the atmosphere or used for EOR operations.

Enhanced oil recovery operations offer opportunities to research carbon storage technologies while providing valuable information about optimizing the recovery of additional oil. In Otsego County, EOR operations are taking place within pinnacle reefs also known as Niagaran reefs. These reefs are highly contained geologic structures that are present at a depth of approximately 5,000–6,000 feet below the ground surface. Many of these reefs are greatly depleted and no longer produce economic amounts of oil. Therefore, they are expected to be excellent containers for geologic CO_2 storage. The MRCSP project is aimed at advancing monitoring and modeling techniques important for proving the security of CO_2 storage. Several different reefs at various stages of development will be tested to better understand both CO_2 storage and EOR potential.

Niagaran Reef Oil Well at MRCSP large-scale field project site.



3-D Seismic Survey used to delineate reef structures at MRCSP large-scale field project site.

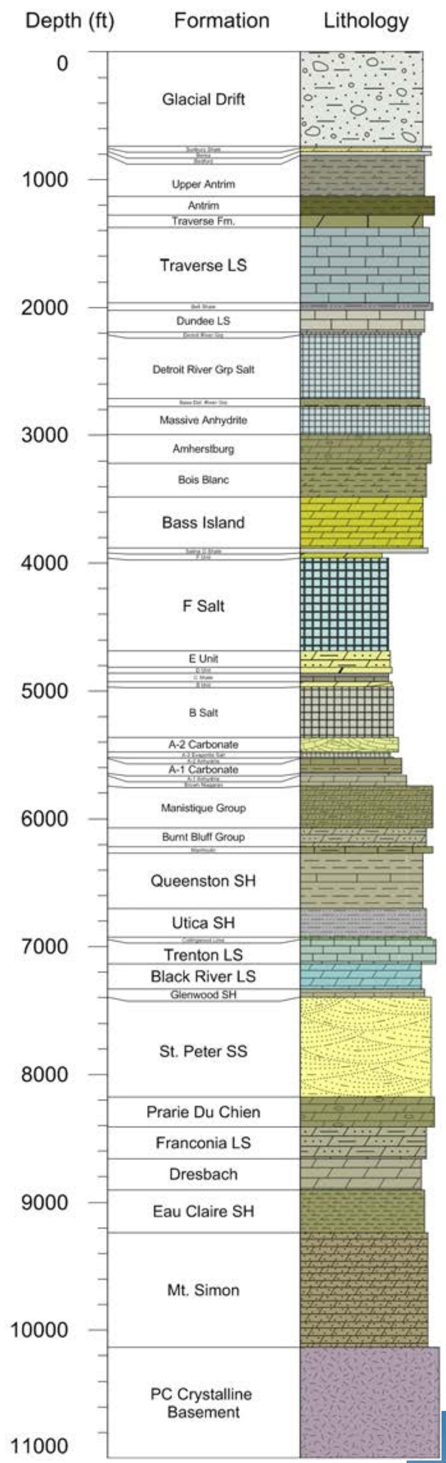


Large-scale field project schematic.

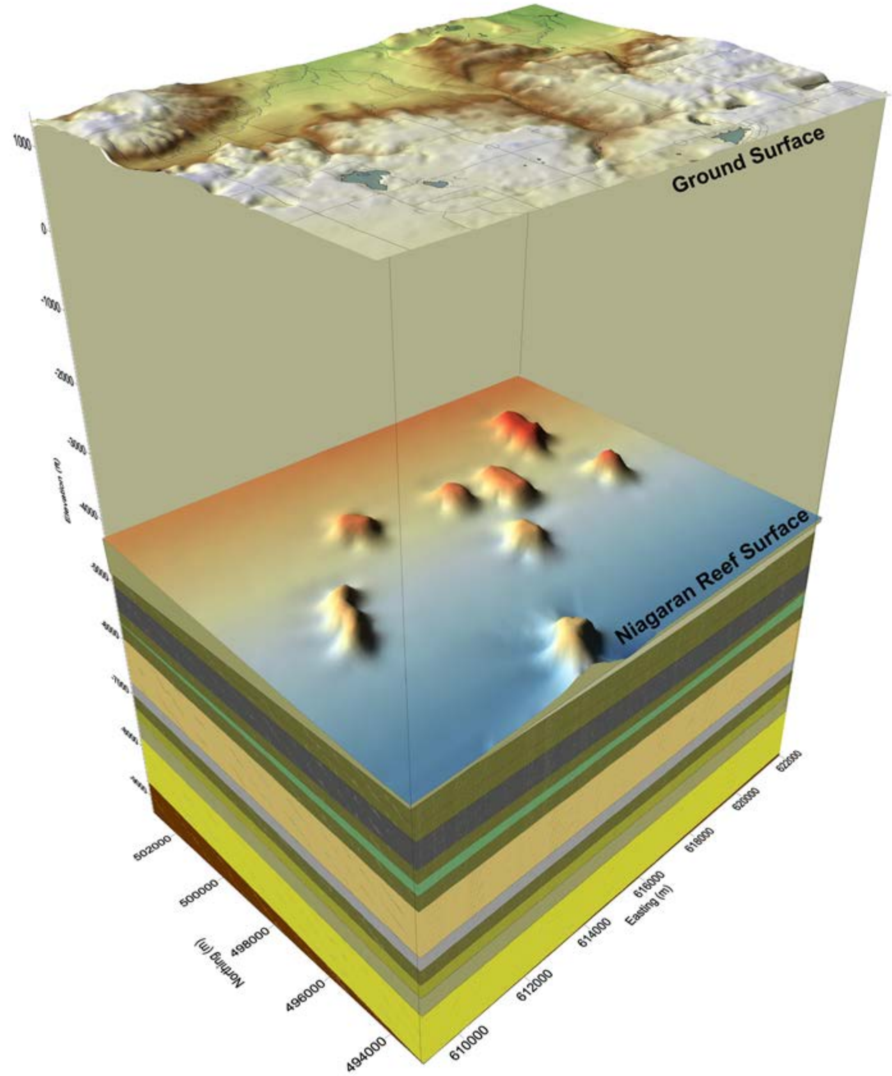
MRCSP Large-Scale Field Project – Injection and Monitoring Strategy

The MRCSP large-scale field project will inject 1 million metric tons (1.1 million tons) of CO_2 into oil fields at different stages in their life cycles. CO_2 injection and monitoring operations will be carried out for three categories of Niagaran reefs distinguished by different stages in the life cycle of EOR.

Category 1 Niagaran reefs are late-stage CO_2-EOR reefs that have undergone extensive primary and secondary oil recovery and are mostly depleted of oil but are still economic, especially if large volumes of low cost CO_2 was available. Category 2 Niagaran reefs are operational EOR reefs that have finished primary oil recovery and are currently undergoing secondary oil recovery using CO_2. Wells and pipelines will be instrumented to obtain geologic and operational data that will be used to validate reservoir simulation models and provide material balances on EOR to determine how much CO_2 the formations retain. Category 3 Niagaran reefs are newly targeted reefs that have typically undergone primary oil recovery, but in which no secondary oil recovery using CO_2 has been attempted. MRCSP will have the opportunity to piggyback on new wells drilled into these reefs for CO_2-EOR operations, which will allow the collection of extensive core samples, advanced wireline logs, and advanced reservoir well tests.



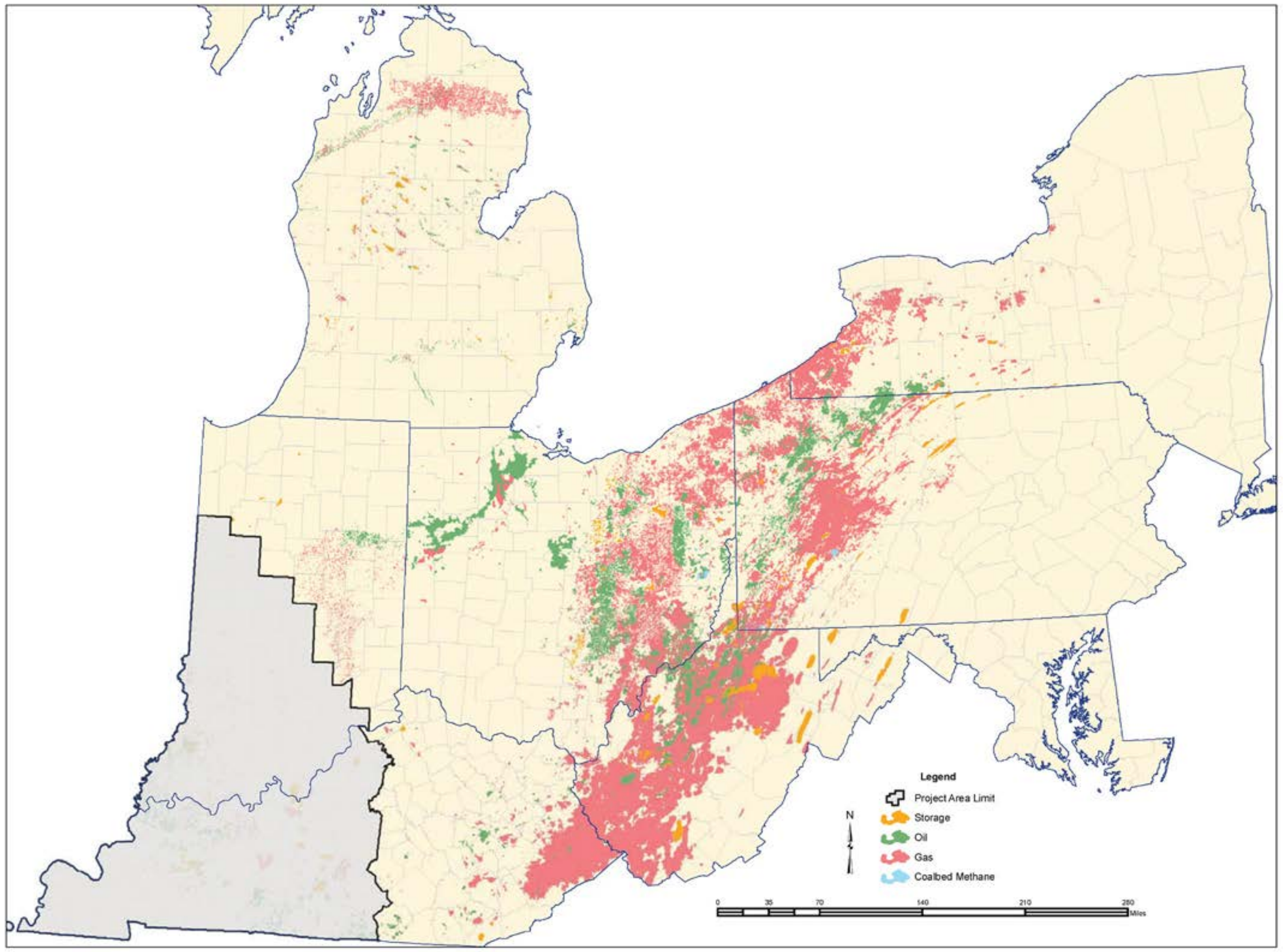
Geologic column of rock layers at MRCSP Development Phase Site.



3-D diagram showing Niagaran reef structures.

CO_2 separation and purification equipment at MRCSP large-scale field project site.

Deep rock units testing and monitoring at MRCSP large-scale field project site.



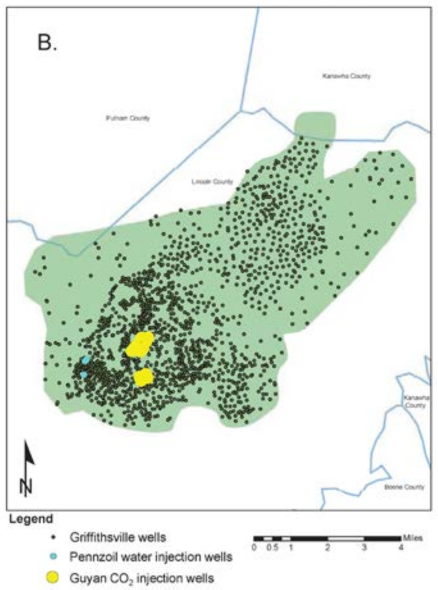
Oil and gas fields are present through much of the MRCSP region. Most of the region's gas storage fields were once producing gas fields. Gas storage fields provide a great analogue for study when examining CO_2 storage.

Commercializing CCUS in the MRCSP Region

The MRCSP region has many large anthropogenic CO_2 stationary sources in close proximity to the region's geologic CO_2 storage resources, making them potential candidates for CCUS commercialization. These opportunities include ethanol plants, new coal-fired power plants, retrofitting existing coal-fired power plants, coal to liquid facilities, EOR, steel plants, cement plants, refineries, landfills, and gas processing facilities. MRCSP analysis has also shown that there are a number of emerging technologies that show promise for improving the economics of CO_2 capture. The region's industrial makeup has provided impetus toward moving forward with CCUS, with several projects in various stages of development.

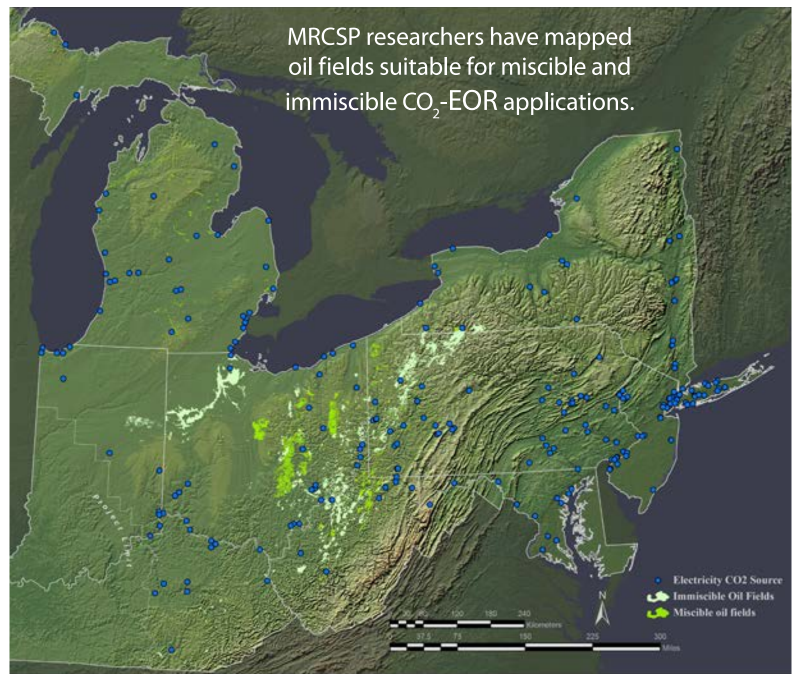
Many oil fields in the MRCSP region are candidates for CO_2-EOR. Criteria in determining potential candidates for CO_2 miscible floods include depth, oil gravity, cumulative production, net pay thickness, and minimum miscibility pressure. Within the project area, ongoing CO_2 injection projects include the Niagaran reef reservoirs (Silurian) in Michigan's Dover field and the Keefer Sandstone reservoir (Silurian) in the Big Andy field in Kentucky. Pilot CO_2 floods in the Big Injun and Berea Sandstone (Mississippian and Devonian) were conducted in the late 1970s and early 1980s in West Virginia. Some reservoirs in the region have more than 90 percent of the original oil remaining in place and a large potential for additional production. There is also potential for ECBM recovery in portions of West Virginia, Pennsylvania, Kentucky, and Ohio. In the MRCSP states, dedicated CO_2 pipelines will be the primary means of transporting CO_2 from the stationary source to a suitable, long-term geologic storage site. While little CO_2 pipeline exists in the region, an extensive natural gas distribution network is present, with an established technical and regulatory framework.

Coalbed methane wells like the one shown here are present in much of the MRCSP region.



Pilot-scale CO_2-EOR field project in West Virginia.

MRCSP researchers have worked with oil and gas operators to evaluate CO_2 storage zones in petroleum exploration wells.



MRCSP researchers have mapped oil fields suitable for miscible and immiscible CO_2-EOR applications.

Integrating CCUS into the MRCSP Community

The MRCSP outreach program was designed to build a foundation of public awareness for carbon storage. The MRCSP approach relied on insight from social science literature involving the role of values and perceptions in developing opinions about a new technology, as well as principles of good science communication. Surveys in the United States and abroad provided empirical data about factors affecting public acceptance of carbon storage.

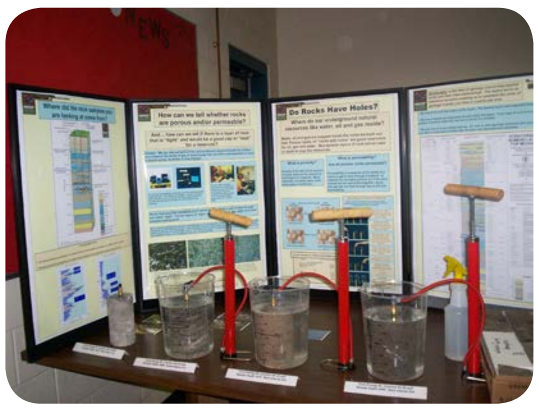
A stakeholder outreach effort to communicate project progress to the local community, general public, and scientific community was undertaken with each small-scale field project in Ohio, Kentucky, and Michigan. This effort involved identification of stakeholders, proactive engagement with these stakeholders, and development of informational materials. An outreach team that included members from each host site was established to develop a site-specific strategy and outreach plan for key stages of the project. Team members provided diverse perspectives upon which the project could draw—technical understanding of planned activities, invaluable knowledge about local culture and politics, and experience for effectively communicating with local residents.

The outreach team provided contact points in the local area and project-related information on the MRCSP website. The host sites held informational meetings for nearby residents, including a series of exhibits and take-home materials, as well as opportunities for one-on-one discussions with technical staff. Other activities included facility tours for partnership members and media interactions. All three of the small-scale geologic storage field projects were completed successfully in terms of relations with industrial hosts, outreach to the local communities, permitting, and test logistics.

MRCSP members at the East Bend Electricity Generating Station, Kentucky, to observe the geologic storage demonstration.

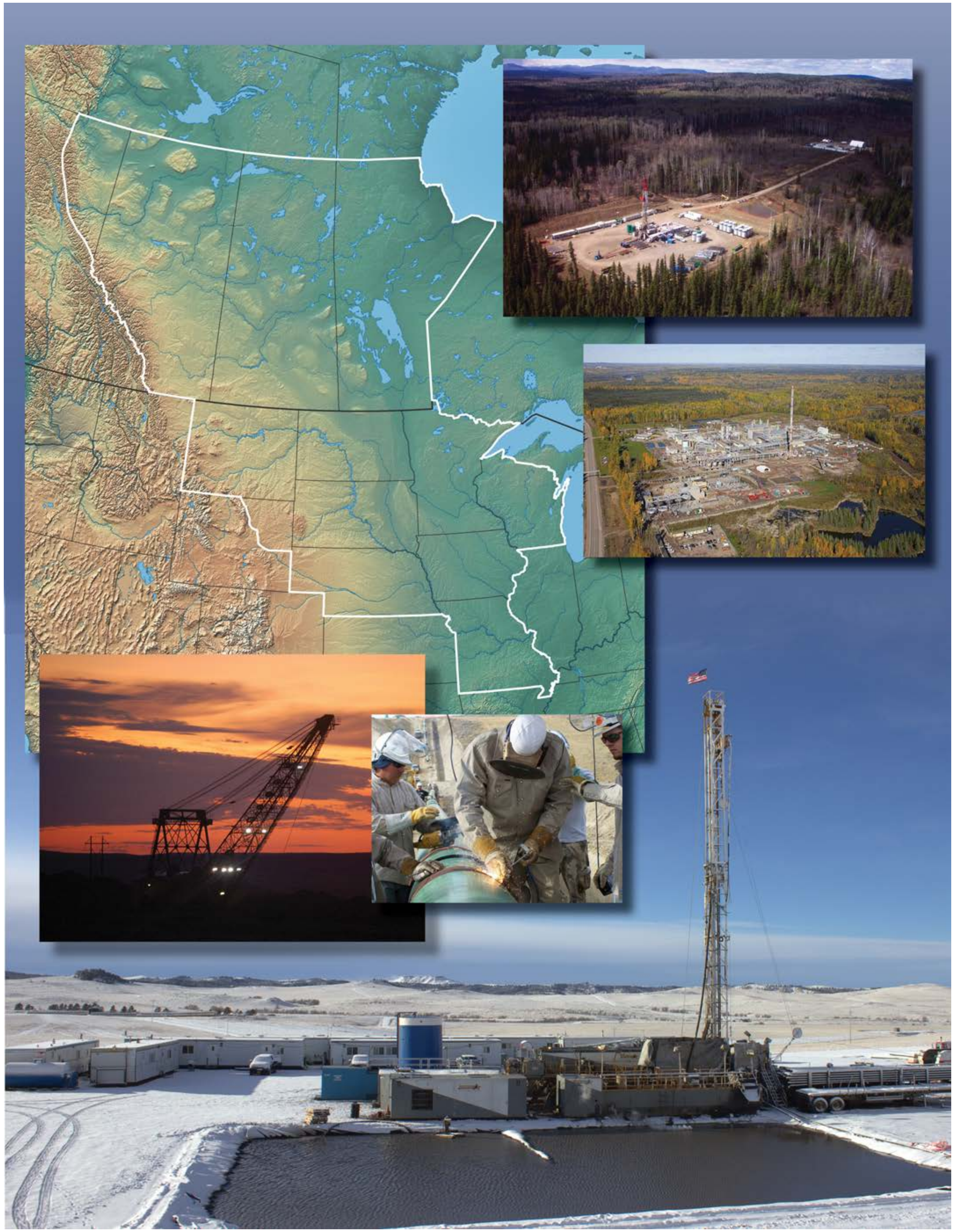
Tour stop at the DTE gas processing plant during an MRCSP Partners meeting in Michigan.

Visitors examine an MRCSP CO_2 injection well in action.



Hands-on display developed by Western Michigan University to communicate key geologic concepts.

Open house for neighbors at the East Bend Electricity Generating Station in Kentucky.



The Plains CO_2 Reduction Partnership

The Plains CO_2 Reduction (PCOR) Partnership, comprising state agencies; coal, oil and gas, and other private companies; electric utilities; universities; and nonprofit organizations, covers an area of more than 1.4 million square miles in the central interior of North America and includes all or part of nine U.S. states and four Canadian provinces.

The PCOR Partnership region has stable geologic basins that are ideal storage targets for CCUS. These basins have been well characterized because of commercial oil and gas activities and have significant CO_2 storage resource. The region's energy industry is evaluating carbon management options, including CCUS. Many of the region's oil fields could develop CO_2-based EOR projects if CO_2 were more readily available. CO_2-based tertiary EOR projects offer a means of developing the expertise and infrastructure required to make CCUS a commercial reality.

The PCOR Partnership's efforts include MVA support at two large-scale, depositionally different demonstration sites. The first demonstration involves the injection of CO_2 into a saline formation in northeastern British Columbia, Canada. The second demonstration will inject CO_2 in the Powder River Basin in southeastern Montana for the dual purpose of CO_2 storage and EOR, ultimately documenting the permanence of underground CO_2 storage. The sources of CO_2 in both demonstrations are natural gas-processing facilities. The PCOR Partnership also continues to provide widespread CCUS outreach and education, aid in regulatory development, and collaboratively undertake regional characterization efforts, including the basal Cambro-Ordovician saline system in the United States and Canada.

PCO2R Partnership

Contact

If you have any questions, comments, or would like more information about the PCOR Partnership, please contact:

http://www.undeerc.org/pcor/

Collage showing the PCOR Partnership region and associated activities.

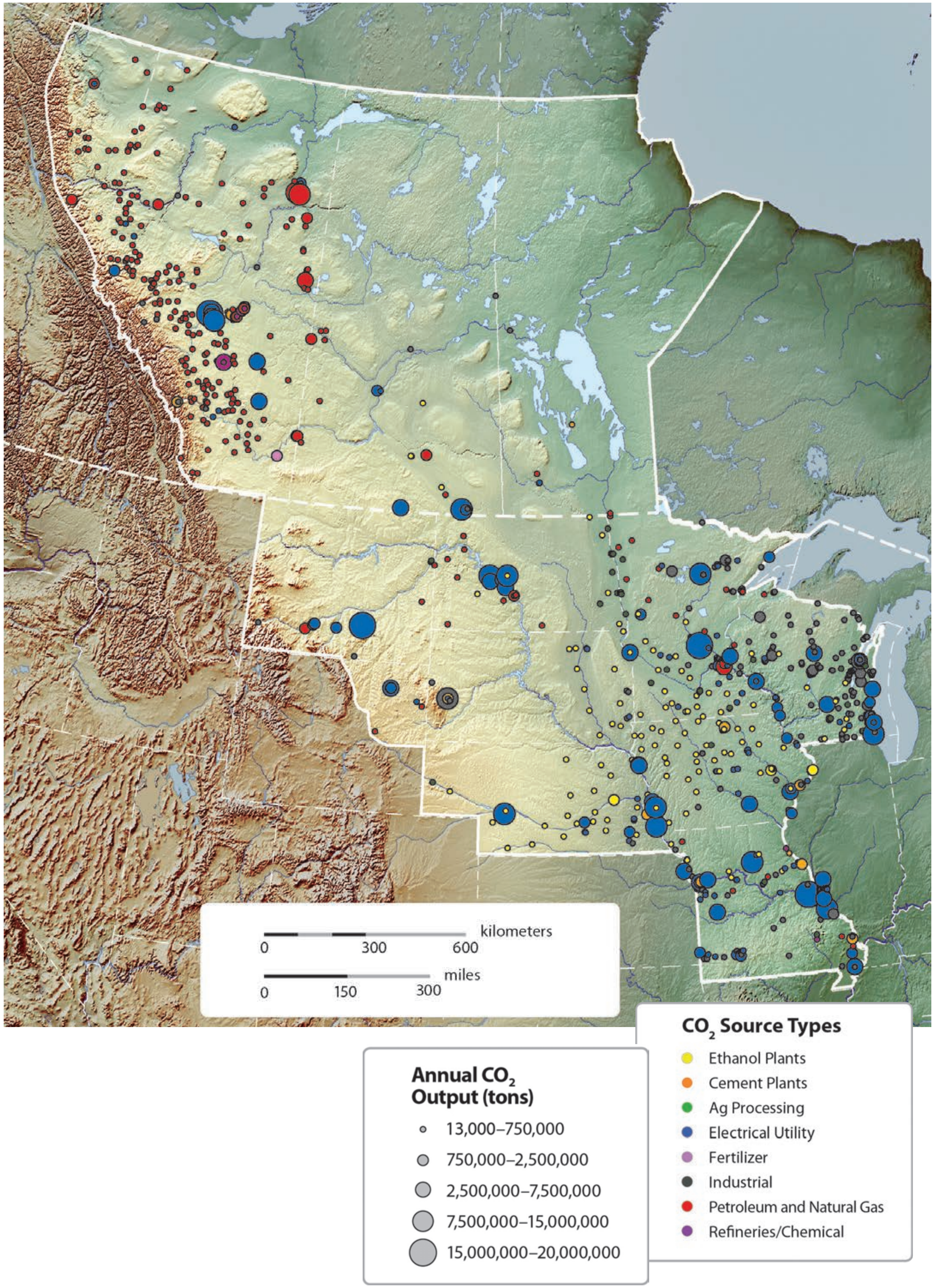
PCOR Partnership CO_2 Sources

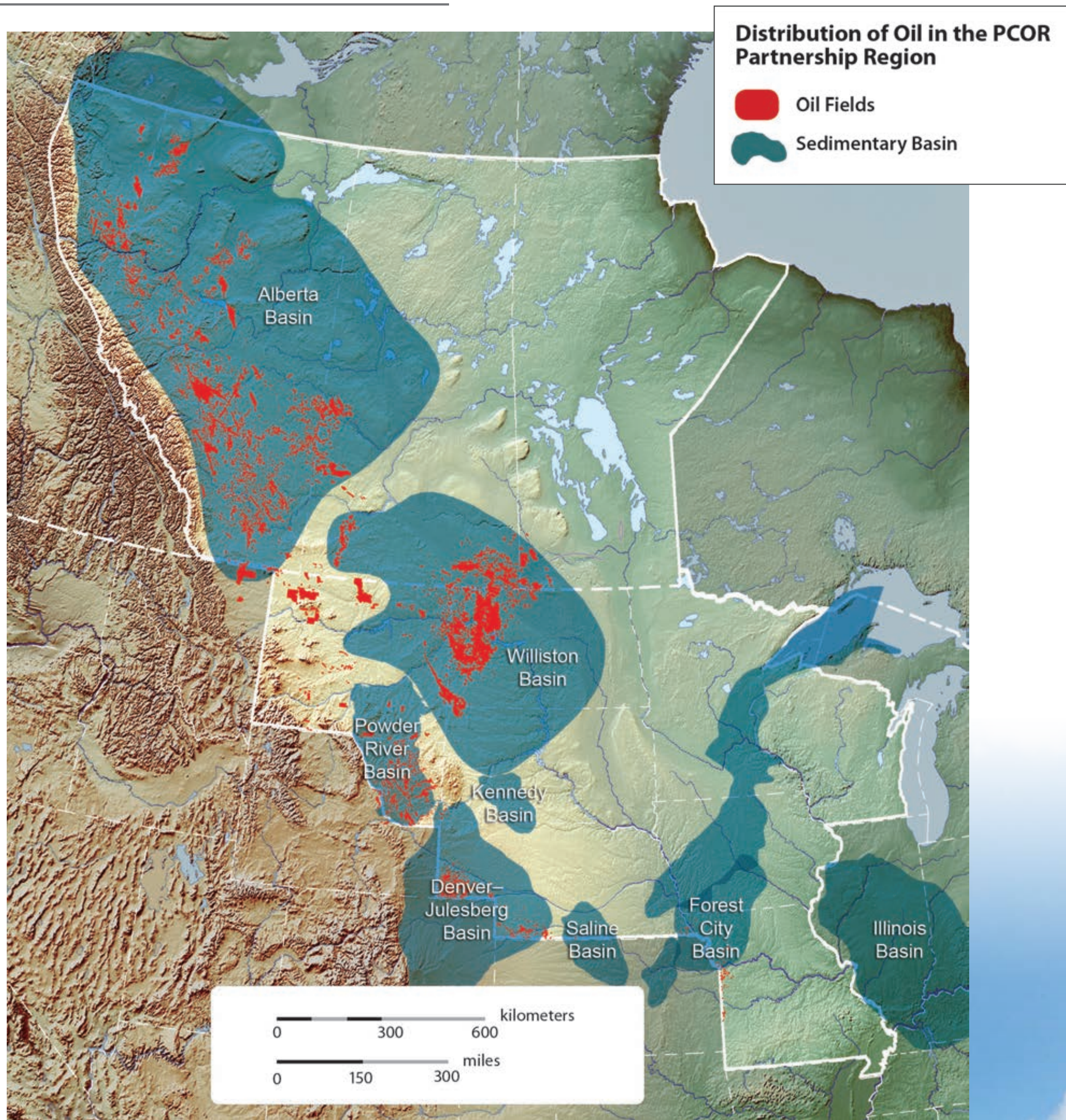
The PCOR Partnership has identified, quantified, and categorized 1,033 stationary sources in the region that have an individual annual output of more than 13,600 metric tons (15,000 tons) of CO_2. Combined, these stationary sources have an annual CO_2 output of approximately 562 million metric tons (619 million tons).

The annual output from the various large stationary sources ranges from less than 90,700 metric tons (100,000 tons) for industrial and agricultural processing facilities that make up the majority of the sources in the region, up to approximately 16.3 million metric tons (18 million tons) for the largest coal-fired electric generation facility. Fortunately, many of the large stationary sources are located in areas favorable for CO_2 storage because of their concurrence with deep sedimentary basins, such as those areas in Alberta, Saskatchewan, North Dakota, Montana, and Wyoming.

The geographic and socioeconomic diversity of the PCOR Partnership region is reflected in the diversity of the CO_2 sources found there. CO_2 is emitted from electricity generation; energy exploration and production activities; agricultural processing; fuel, chemical, and ethanol production; and various manufacturing and industrial activities. While the CO_2 emissions from the individual PCOR Partnership stationary sources are no different from similar sources located around North America, the wide range of source types within the PCOR Partnership region offers the opportunity to evaluate the capture, transport, and storage of CO_2 in many different scenarios.

Estimated CO_2 Emissions by State/Province in the PCOR Partnership		
State/Province	**Tons CO_2/yr**	**Metric Tons CO_2/yr**
Alberta	133,359,973	120,981,501
British Columbia	5,870,826	5,325,896
Iowa	70,943,370	64,358,406
Manitoba	1,435,710	1,302,447
Minnesota	60,904,019	55,250,908
Missouri	103,866,292	94,255,422
Montana	22,135,547	20,080,926
Nebraska	46,194,005	41,906,277
North Dakota	40,104,178	36,381,708
Saskatchewan	23,849,202	21,635,519
South Dakota	18,404,319	16,696,030
Wisconsin	84,415,980	76,580,489
Wyoming	8,303,387	7,532,666
TOTAL	**619,786,808**	**562,258,195**





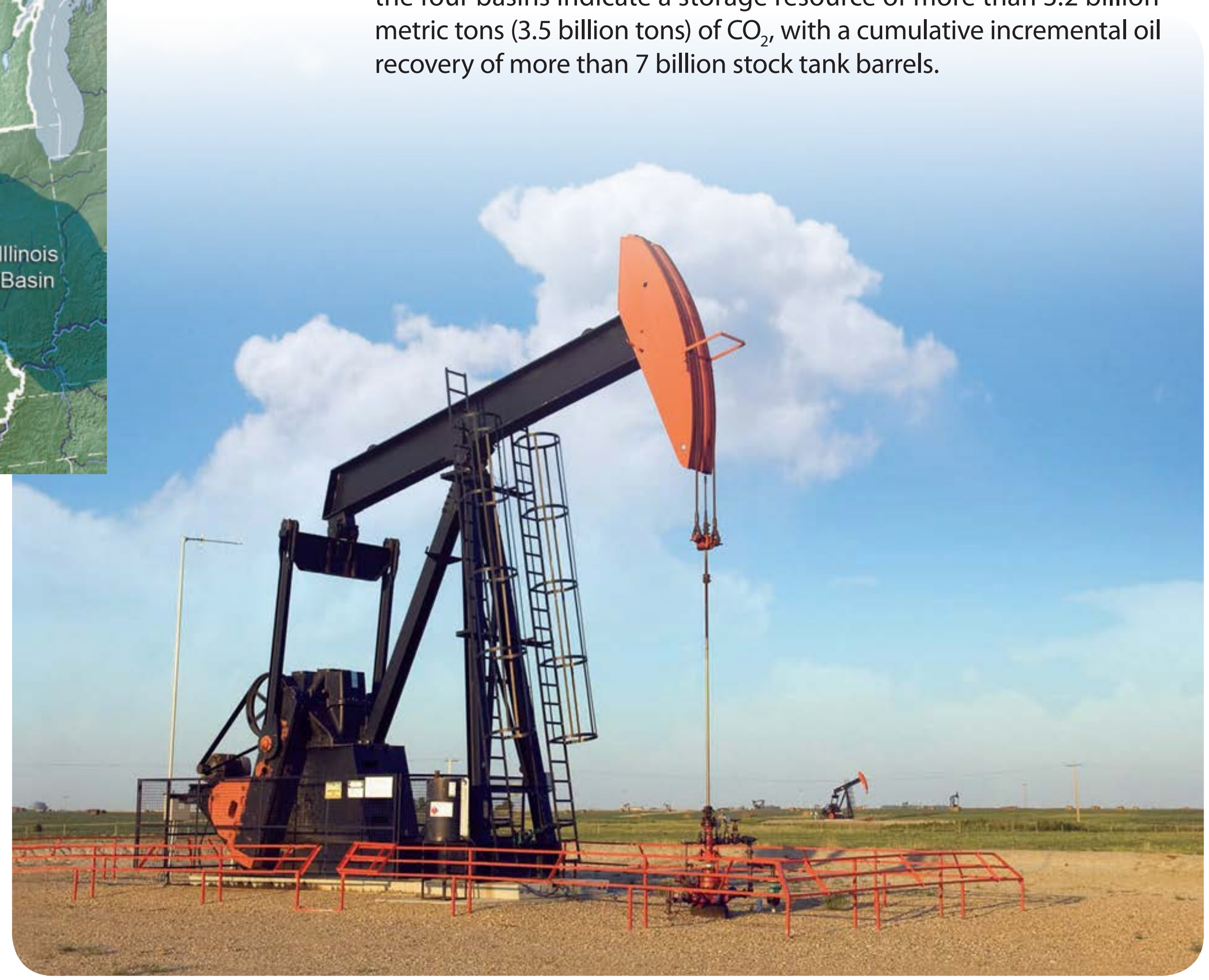
PCOR Partnership Oil and Gas Reservoirs

Although oil was first discovered in the PCOR Partnership region in the late 1800s, significant development and exploration did not begin until the late 1920s. The body of knowledge gained in the nearly 90 years of exploration and production of hydrocarbons in this region is an important step toward understanding the mechanisms for securely storing large amounts of CO_2. Today, oil is drawn from the many oil fields in the PCOR Partnership region at depths ranging from 200 feet to 16,000 feet.

Reconnaissance-level CO_2 storage capacities were estimated for selected oil fields in the Williston, Powder River, Denver-Julesberg, and Alberta Basins. Two calculation methods were used, depending on each field's available reservoir characterization data. The estimates were developed using reservoir characterization data obtained from the petroleum regulatory agencies and/or geologic surveys from oil-producing states and provinces in the PCOR Partnership region. Using a volumetric method, estimates for fields evaluated in the four basins indicate a storage resource of more than 3.2 billion metric tons (3.5 billion tons) of CO_2, with a cumulative incremental oil recovery of more than 7 billion stock tank barrels.

Estimated CO_2 Storage Resource in Depleted Oil and Gas Reservoirs in the PCOR Partnership

State/Province	CO_2 Storage Volume (billion metric tons)
Alberta	10
Manitoba	1
Montana	2
Nebraska	< 1
North Dakota	4
Saskatchewan	7
South Dakota	< 1
Wyoming	1
Total	**26**



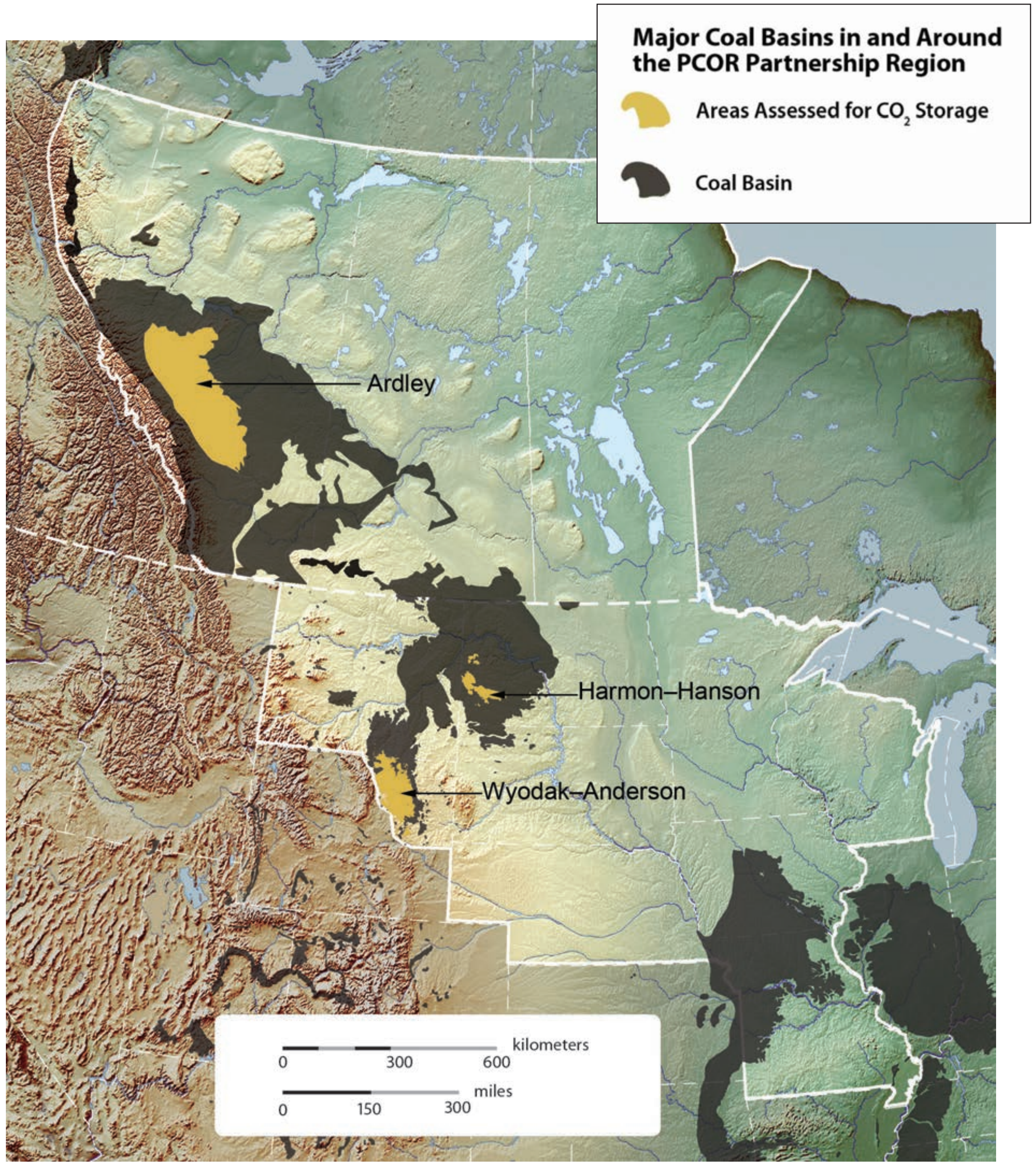
Pump jack in the PCOR Partnership region.

PCOR Partnership Unmineable Coal

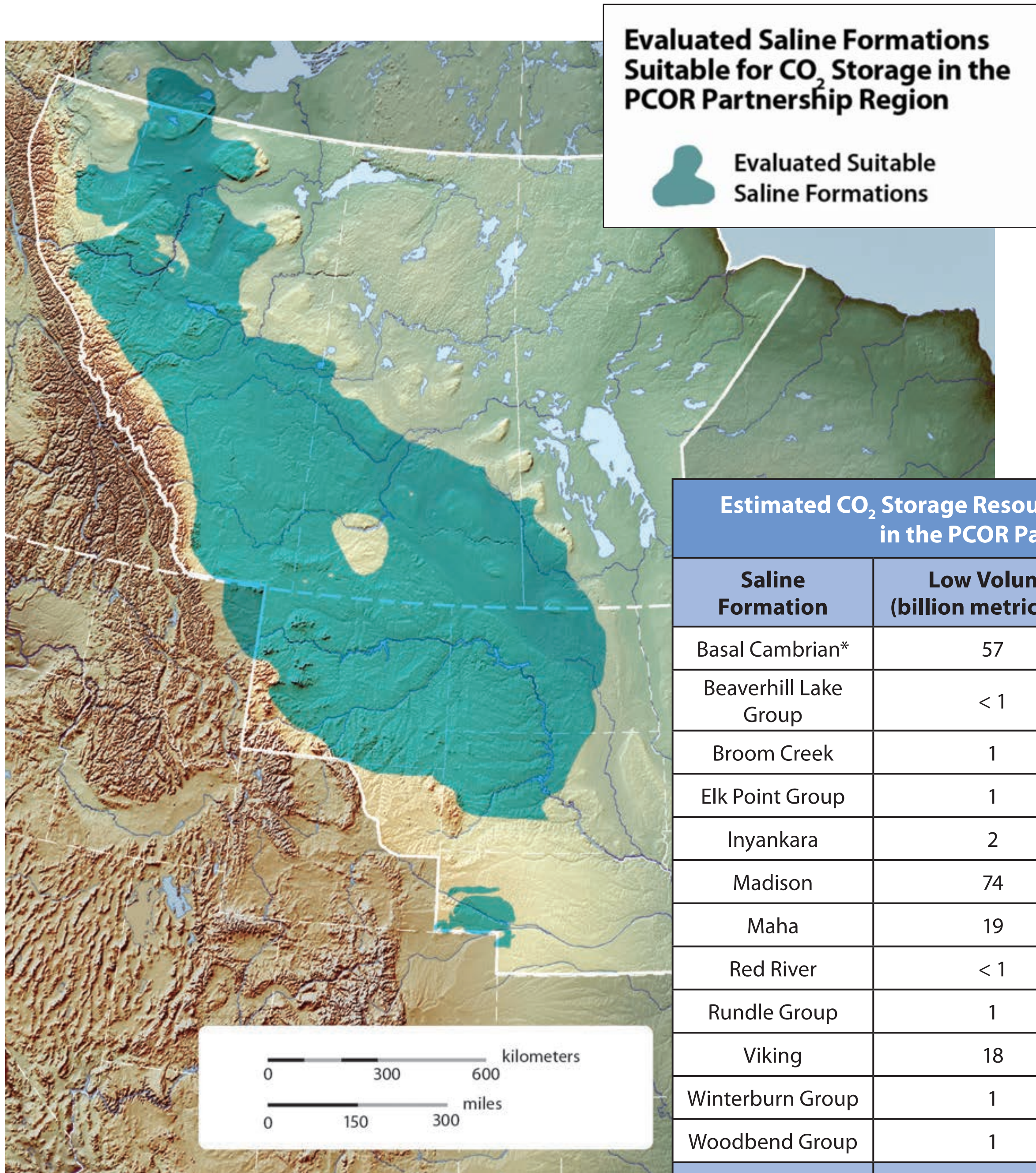
The PCOR Partnership region is home to large resources of coal. Much of this resource is used to generate electricity at coal-fired power plants in the region and beyond. However, a significant portion of this resource lies at depths that are not economically recoverable. Just as with depleting oil reservoirs, unmineable coal in the region may be a good opportunity for CO_2 storage.

Three deep, major coal horizons in the PCOR Partnership region have been characterized with respect to CO_2 storage: the Wyodak-Anderson bed in the Powder River Basin, the Harmon-Hanson interval in the Williston Basin, and the Ardley coal zone in the Alberta Basin. The total maximum CO_2 storage resource potential for all three coal deposits is approximately 7.3 billion metric tons (8 billion tons). In the Powder River Basin area of northeastern Wyoming, the CO_2 storage potential for areas where the coal overburden thickness is greater than 1,000 feet could store all of the current annual CO_2 emissions from nearby power plants for approximately the next 150 years.

Field inspection of freshly collected lignite core.



Estimated CO_2 Storage Resource in Unmineable Coal by Coal Seam in the PCOR Partnership	
Coal Seam	**Estimated CO_2 Storage Volume (million metric tons)**
Ardley	29
Harmon-Hansen	543
Wyodak-Anderson	6,242
Total	**6,814**



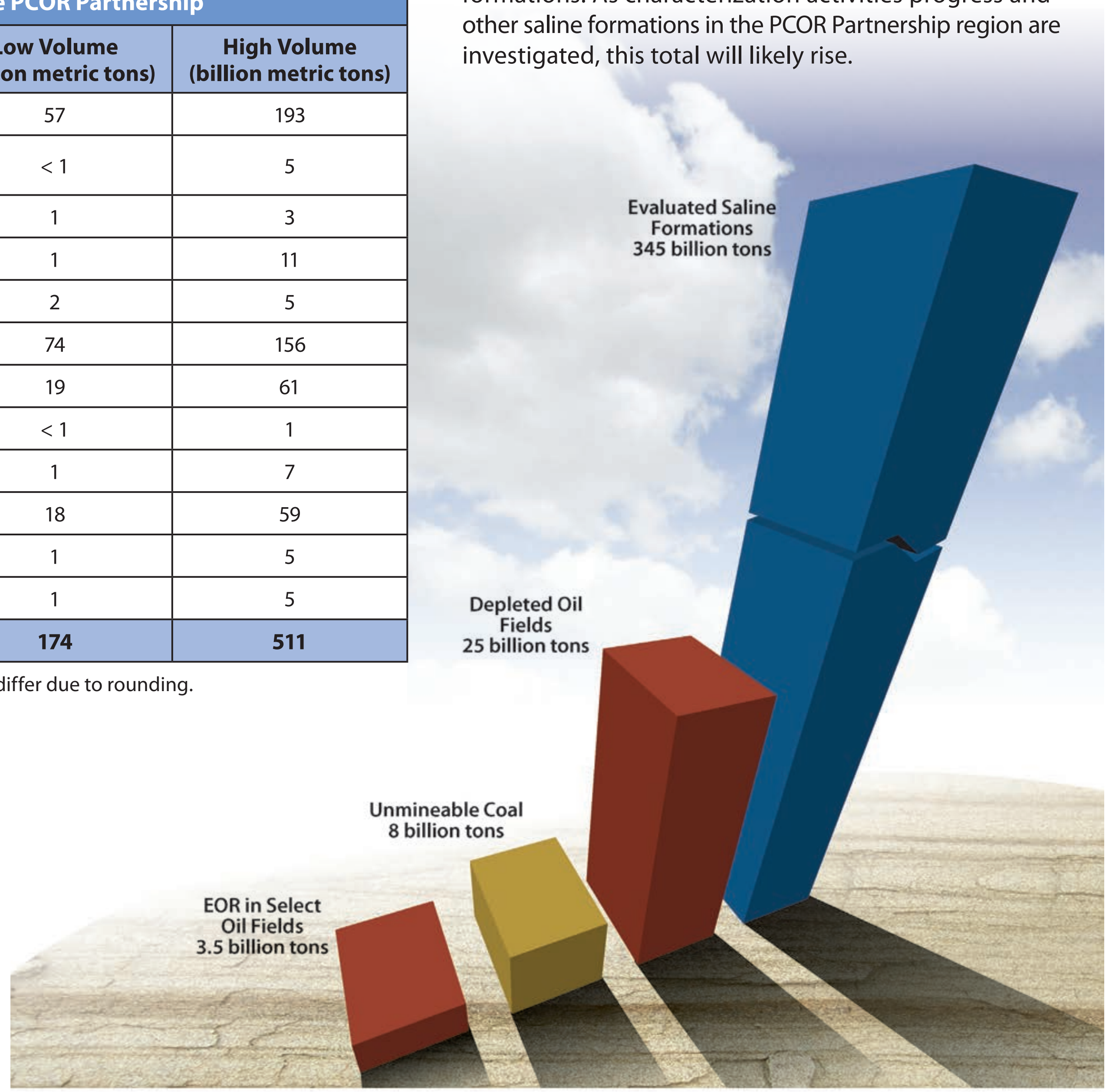
PCOR Partnership Saline Formations

Deep saline formations within the PCOR Partnership region have the potential to store large quantities of anthropogenic CO_2. Through the course of characterization activities associated with the PCOR Partnership program and the efforts of its partners in Canada, several saline formations have been evaluated to determine the magnitude of the CO_2 storage resource available. In many sedimentary basins, multiple potential targets for CO_2 storage may exist within a defined geographic area, each with an appropriate seal to ensure safe, long-term storage. The basins in the PCOR Partnership region follow this configuration of stacked target formations. The extent of the areas identified for potential storage are constrained by depth (to ensure optimal density of the injected CO_2) and by salinity (to avoid protected groundwater resources). To date, reconnaissance-level characterization has identified 313 billion metric tons (345 billion tons) of potential storage in deep saline formations. As characterization activities progress and other saline formations in the PCOR Partnership region are investigated, this total will likely rise.

Estimated CO_2 Storage Resource in Saline Formations in the PCOR Partnership

Saline Formation	Low Volume (billion metric tons)	High Volume (billion metric tons)
Basal Cambrian*	57	193
Beaverhill Lake Group	< 1	5
Broom Creek	1	3
Elk Point Group	1	11
Inyankara	2	5
Madison	74	156
Maha	19	61
Red River	< 1	1
Rundle Group	1	7
Viking	18	59
Winterburn Group	1	5
Woodbend Group	1	5
Total	**174**	**511**

*Values in the 10K grid may differ due to rounding.



Magnitudes of resource potential for geologic storage of CO_2 in the PCOR Partnership region.

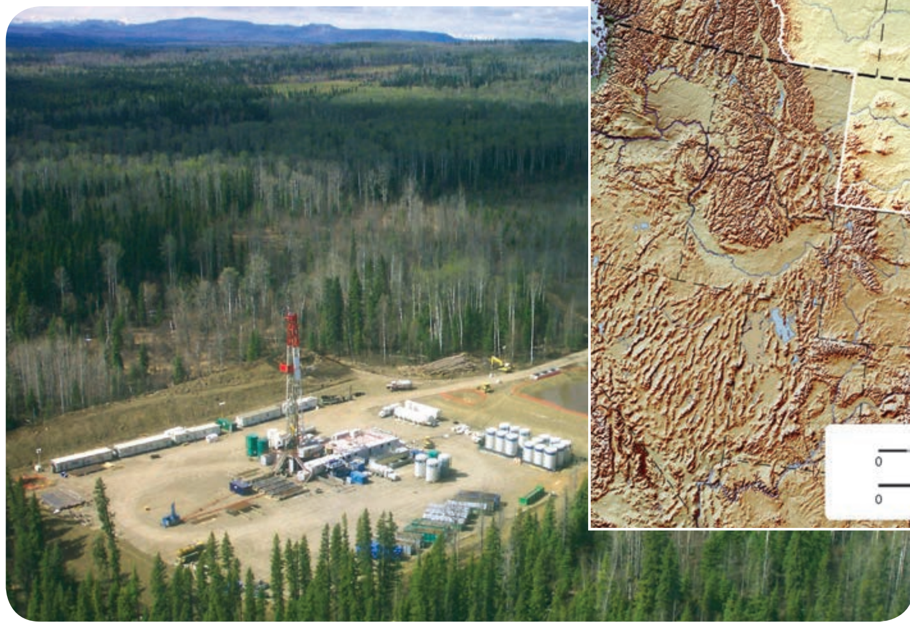
PCOR Partnership Large-Scale Field Projects

Through its role in the RCSP Initiative'sLarge-Scale Field Project, the PCOR Partnership has teamed with industrial partners to conduct two commercial-scale CCUS demonstrations in the region. One of the large-scale tests will demonstrate CO_2 storage in a saline formation, while the other will be a combined CCUS and EOR demonstration project. The sources of CO_2 in both demonstrations are natural gas-processing facilities.

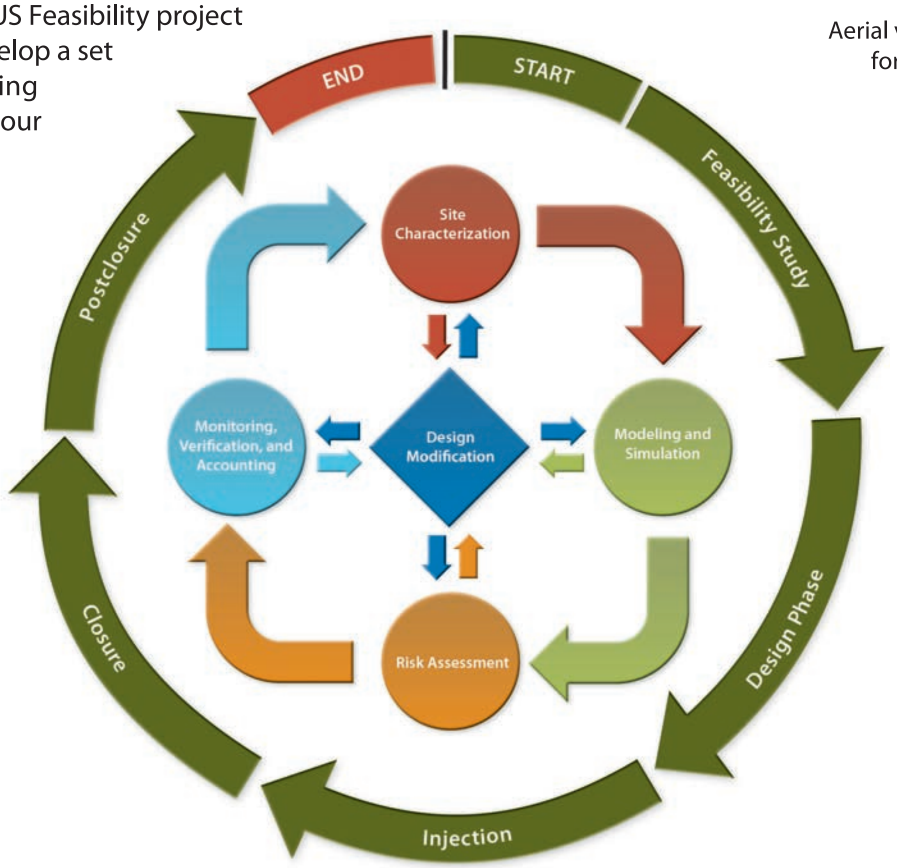
This project is recognized by the Carbon Sequestration Leadership Forum as being uniquely qualified to fill technological gaps with regard to geologic storage of CO_2.

Fort Nelson Demonstration Project

Led by Spectra Energy Transmission, the Fort Nelson CCUS Feasibility project is an international collaboration that includes industry, government, universities, and technologists. The project has initiated a large application of deep saline formation geologic storage and aims to reduce CO_2 emissions from Spectra Energy Transmission's Fort Nelson natural gas-processing plant by injecting approximately 1.8 million metric tons (2 million tons) of CO_2 annually into a deep carbonate formation for long-term geologic storage. The Fort Nelson CCUS Feasibility project provides a unique opportunity to develop a set of cost-effective, risk-based monitoring techniques for large-scale storage of sour CO_2 in deep saline formations.



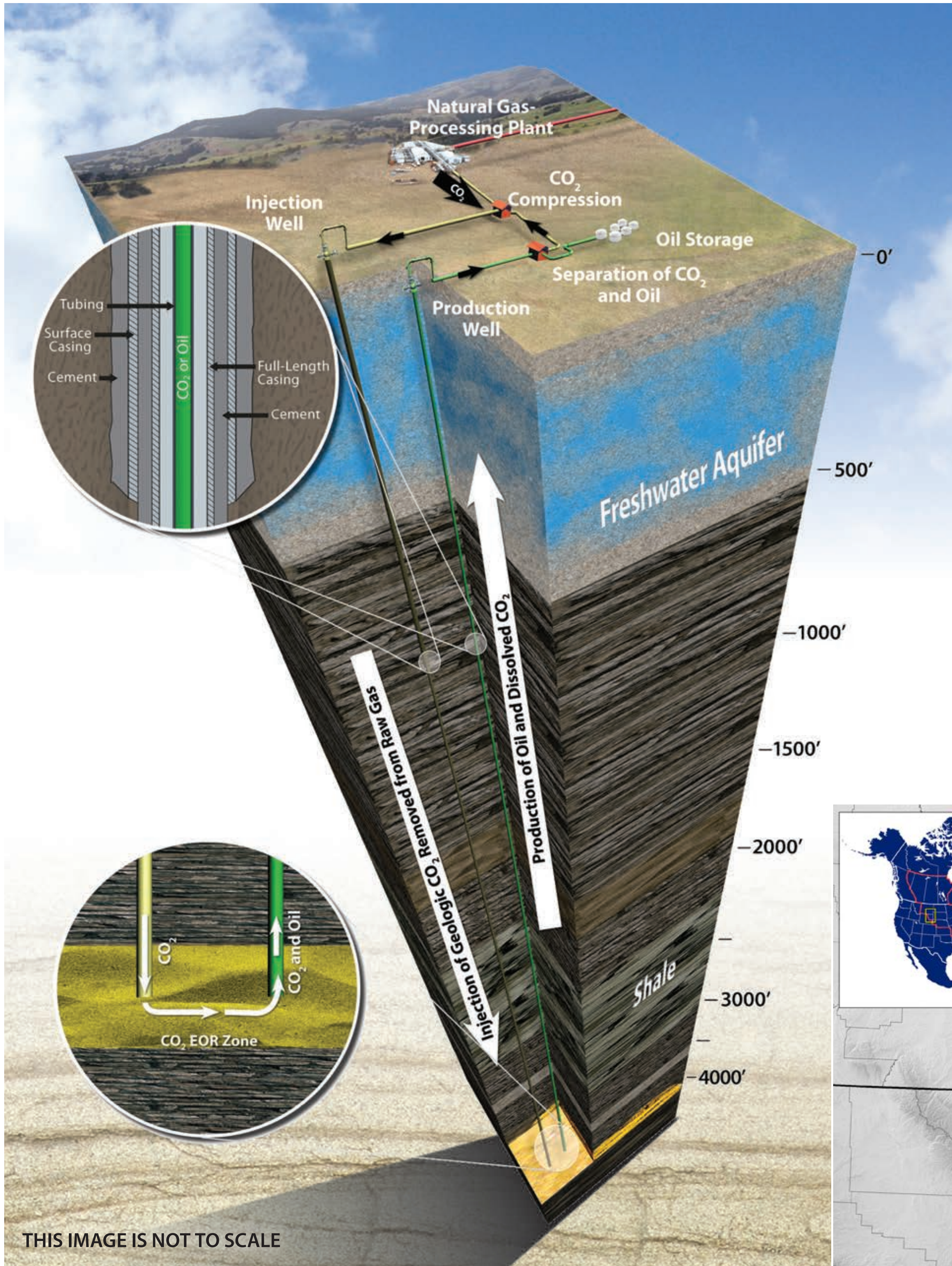
Aerial view of an exploratory well being drilled for the Fort Nelson demonstration project.



PCOR Partnership MVA diagram.

Monitoring, Verification, and Accounting Approach

The PCOR Partnership is developing a philosophy that integrates site characterization; modeling and simulation; risk assessment; and MVA strategies into an iterative process to produce meaningful results for large-scale CO_2 storage projects. Elements of any of these activities are crucial for understanding or developing the other activities. For example, as new knowledge is gained from site characterization, it reduces a given amount of uncertainty in geologic reservoir properties. This reduced uncertainty can then propagate through modeling; risk assessment; and MVA efforts. With this process, the PCOR Partnership program is in a strong position to refine characterization; modeling; risk assessment; or MVA efforts based on the results of any of these activities.



Wells are engineered to protect precious groundwater resources, whether for CO_2 injection or oil production. Well construction is governed by Federal and state regulations. Three layers of steel (casing and tubing) and two layers of durable, long-lasting cement separate the contents from the surrounding groundwater in accordance with Montana regulations.

PCOR Partnership Large-Scale Field Project

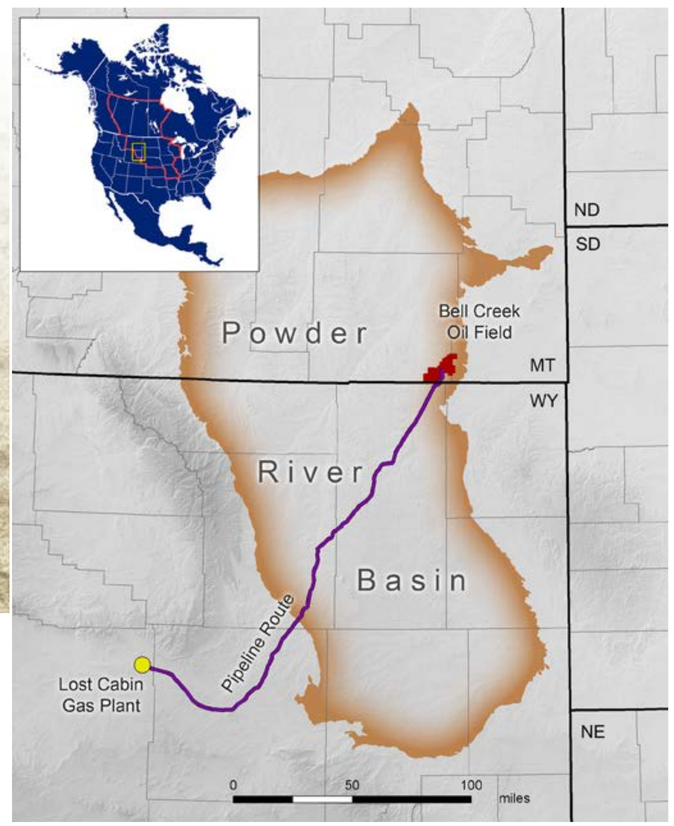
Bell Creek Demonstration Project

Denbury Onshore, LLC, a leader in CO_2-EOR operations, is implementing a commercial CO_2-EOR project that will add 20 or more years and more than 35 million barrels to the life of the Bell Creek oil field in southeastern Montana. A 232-mile pipeline will deliver CO_2 from the Lost Cabin natural gas-processing facility in central Wyoming to the Bell Creek field. CO_2 injection for EOR is scheduled to start during the fourth quarter of 2012.

Denbury teamed with the PCOR Partnership to characterize and model CO_2 behavior in the subsurface as a basis for designing a comprehensive monitoring plan for the CO_2 storage and EOR operation. Detailed site characterization; modeling; subsurface risk analysis; and MVA of the CO_2-EOR and storage operations will allow site operators to account for the CO_2 utilized in oil production and verify that the CO_2 remains in place once EOR operations are complete.

The integrated approach at Bell Creek helps meet the safety expectations of local landowners and communities while reassuring stakeholders that CO_2 will remain securely stored in the formation. Further, by storing CO_2 at the Bell Creek oil field, Denbury protects the environment by decreasing the carbon footprint of its regional oil field operation.

The results of the Bell Creek project will help future projects effectively implement a proven CO_2 MVA system as part of a comprehensive approach to subsurface CO_2 management and EOR operations. The Bell Creek project combines the proven techniques of CO_2-EOR with the characterization and monitoring needed for effective carbon storage. The result is a new standard for safe and practical CO_2-EOR to CO_2 storage operations.



Location of the Bell Creek oil field in southeastern Montana and the pipeline that will transport CO_2 to the field.

Bell Creek Demonstration Project (cont'd)

Monitoring the surface, near-surface, and deep subsurface environment is an essential component of any carbon storage project. The purpose of surface and near-surface monitoring is twofold: (1) to establish pre-injection conditions for naturally occurring CO_2 levels in surface water, soil, and shallow groundwater formations in the vicinity of the carbon storage formation, and (2) to provide data to confirm that surface and near-surface environments remain unaffected by the injection process.

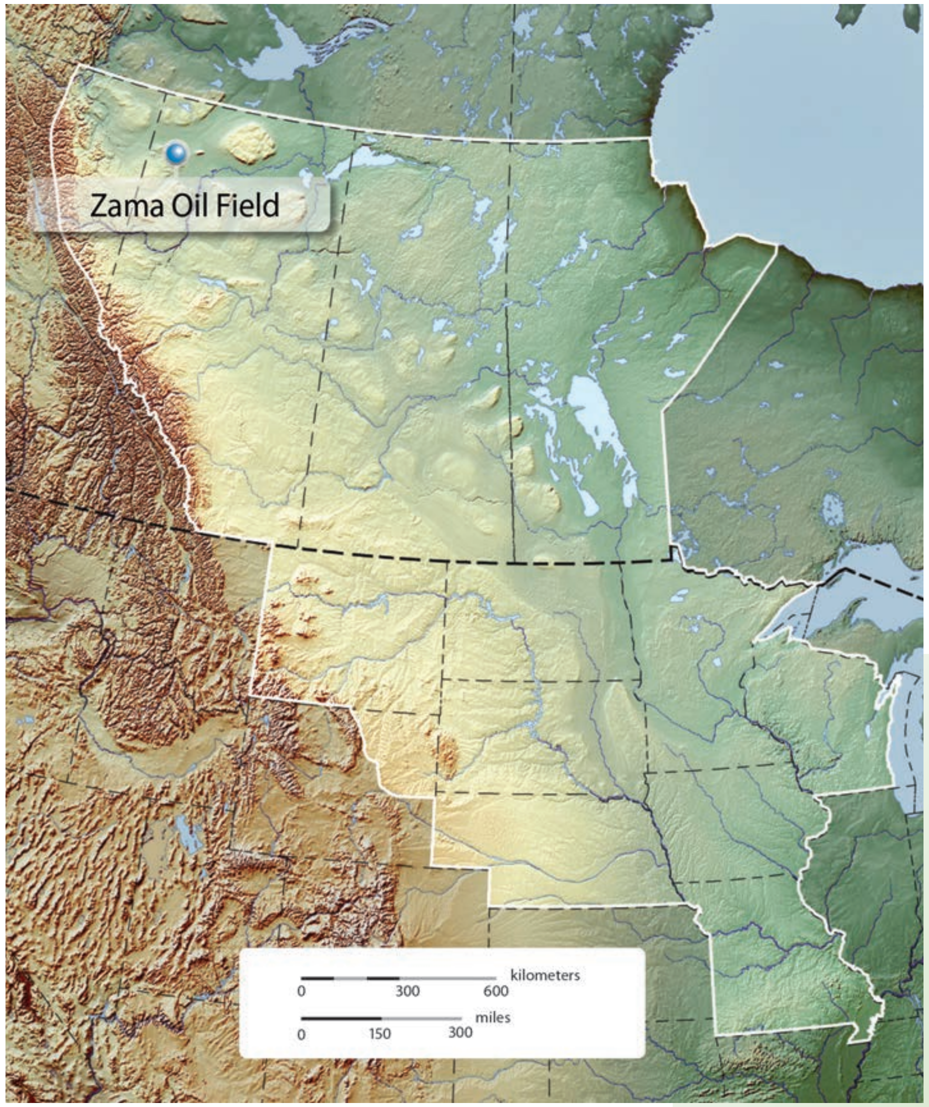
The primary purpose of deep subsurface monitoring is to track the movement of CO_2 in the subsurface in order to evaluate the CO_2 storage efficiency of the CO_2-EOR program, as well as predict and understand the ultimate fate of CO_2 within the storage reservoir. In January 2012, a new observation well was completed. In conjunction with drilling operations, an extensive coring and well logging program was conducted to provide critical data for geologic characterization and reservoir simulation efforts. A combination of permanent downhole monitoring equipment (pressure gauges and fiber optic cable capable of measuring the wellbore temperature profile), time-lapse well logs, seismic surveys, and wellhead pressure and flow rate sensors will provide key information about reservoir behavior and subsurface CO_2 migration and saturations during and after injection.

Collecting a surface water sample to establish baseline conditions in the Bell Creek oil field.

Driving a probe to collect a baseline soil gas sample in the Bell Creek oil field.

Mini vibe trucks conducting a check shot survey as part of a seismic source testing exercise in the Bell Creek oil field.

Drilling the observation well in the Bell Creek oil field.



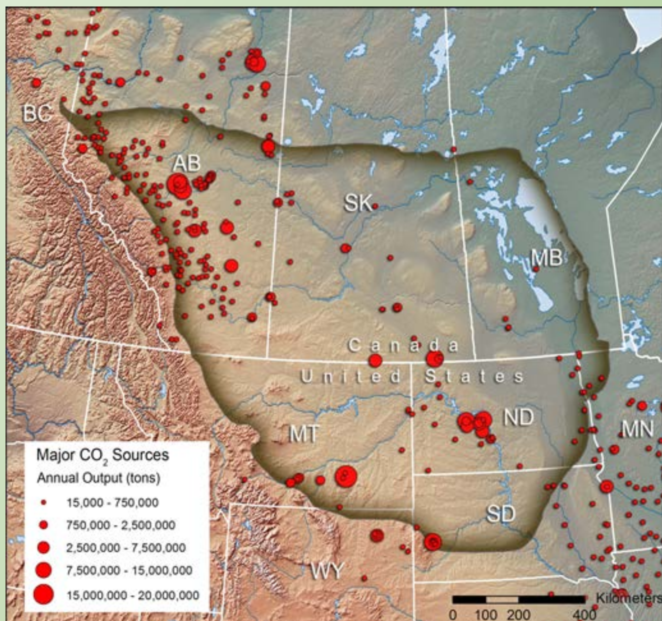
The Zama field small-scale test was recognized by the International Carbon Sequestration Leadership Forum as being uniquely qualified to fill technological gaps with regard to geologic storage of CO_2.

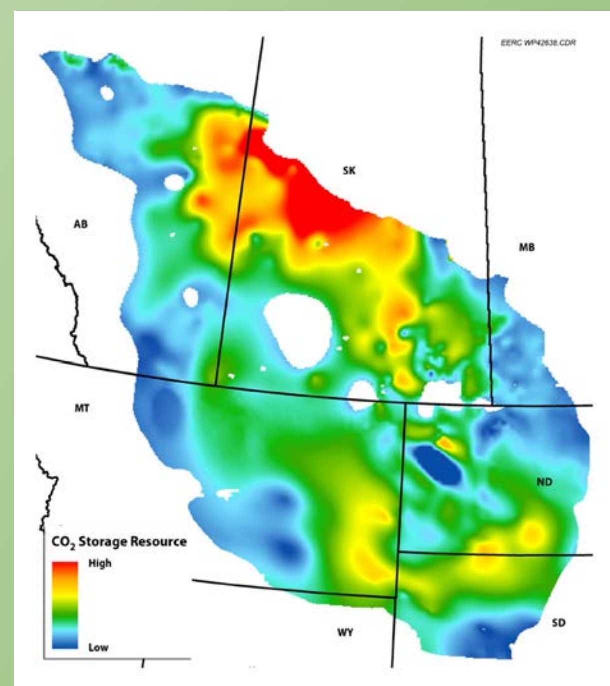
Zama Oil Field

The Zama oil field in northwestern Alberta, Canada, covers an area of nearly 463 square miles. Oil production in the Zama field is primarily from reservoirs in pinnacle reefs. During the small-scale field project portion of the RCSP Initiative, the PCOR Partnership conducted MVA activities at an EOR project focused on a particular pinnacle. In an expanding role, the PCOR Partnership is developing improved static geologic models and conducting detailed dynamic simulations of injection and production at several Zama pinnacles that are undergoing (or have undergone) sour CO_2 injection for EOR. The goal of these efforts is to develop improved estimates of CO_2 storage resource, original oil in place, and recoverable reserves for each of those pinnacles, which in turn will provide more insight regarding the overall potential for CO_2 storage and EOR in the Zama field as a whole.

Basal Cambro-Ordovician Saline System

The PCOR Partnership is currently collaborating with Alberta Innovates–Technology Futures on a bi-national project to characterize and assess the CO_2 storage resource of the basal Cambro-Ordovician saline system, which occurs in large parts of both the United States and Canada. This lowermost saline system underlies many of the area's large stationary CO_2 sources and represents a regionally significant target for CCUS across 517,000 square miles of the central interior of North America. The overall project objectives are to characterize this extensive saline system and evaluate the potential for, and effects of, CO_2 storage in this formation. Results to date indicate a CO_2 storage resource potential of approximately 57 to 193 billion metric tons (63 to 213 billion tons).

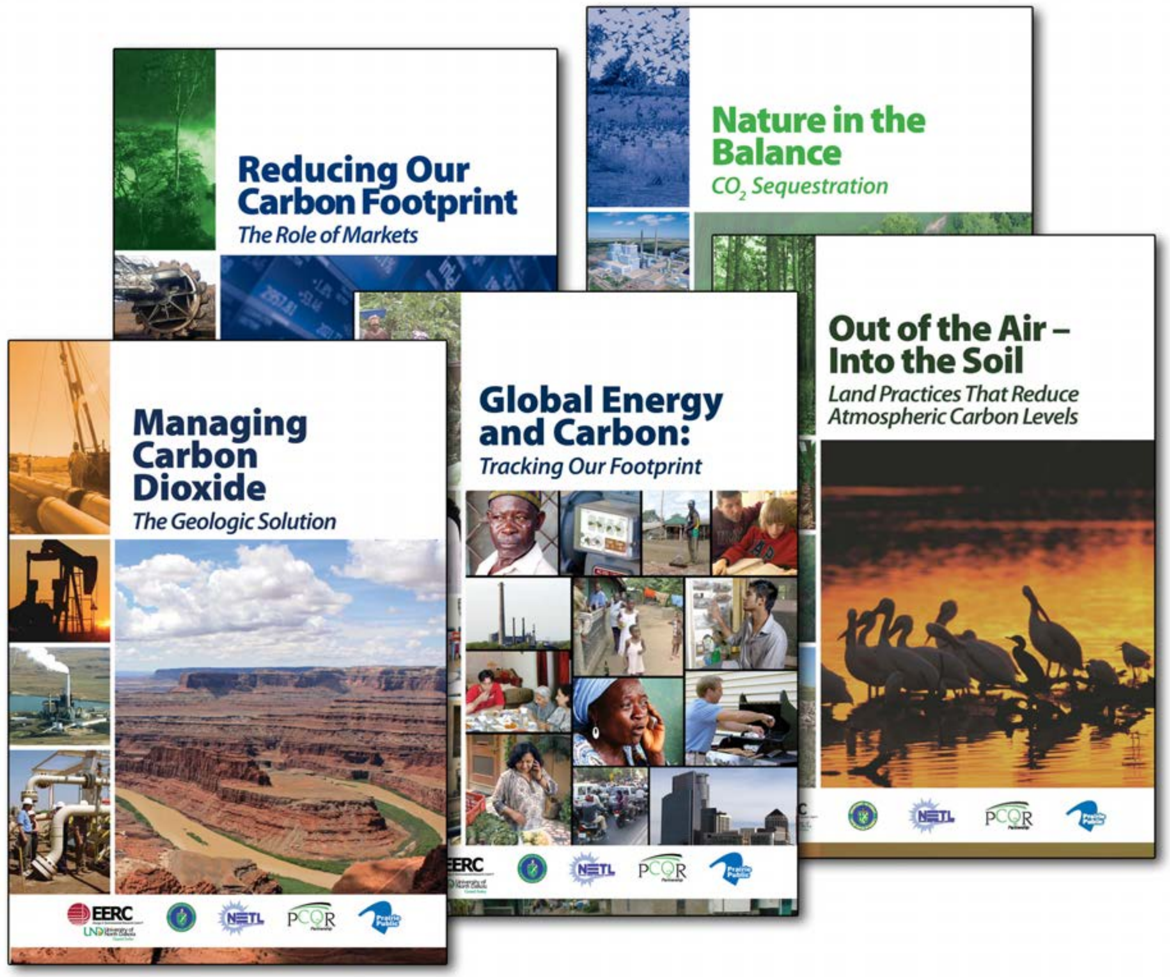




Integrating CCUS into the PCOR Partnership Community

Developing public support for CCUS is an essential component of the RCSP Initiative. The PCOR Partnership is working to increase CCUS knowledge among the general public, regulatory agencies, policymakers, and industry. In addition to a website, factsheets, posters, a regional atlas, news articles, and press releases, the PCOR Partnership teamed with Prairie Public Broadcasting to create an exclusive documentary series about CO_2 and carbon management.

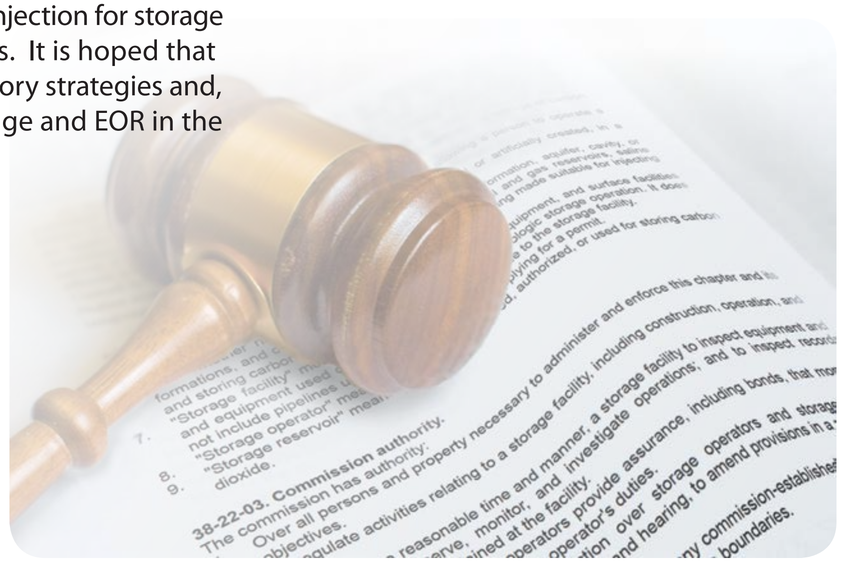
The PCOR Partnership outreach team continues to undertake general public outreach and will support its partners' outreach activities related to the development and implementation of the Partnership's two commercial-scale geologic storage projects.

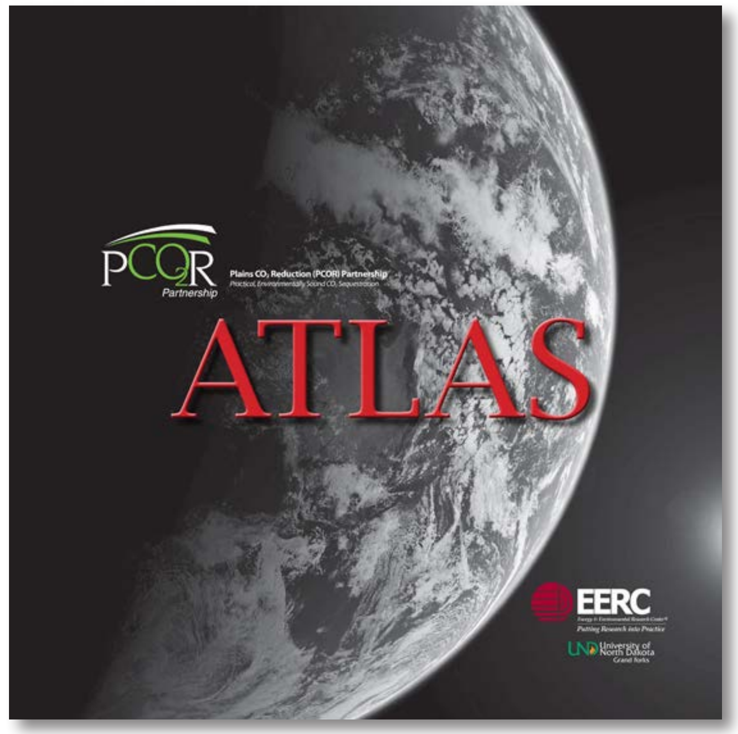


DVD covers of the documentary series produced by the PCOR Partnership and Prairie Public Broadcasting.

PCOR Partnership Permitting and Regulation Activities

The PCOR Partnership continues to regularly interface with relevant regional regulatory agencies, as well as with Federal regulatory agencies in the United States and Canada, to understand the regulatory framework for project implementation. In addition, the PCOR Partnership facilitates activities that allow pertinent entities, including the Interstate Oil and Gas Compact Commission, to gather and exchange of information. For the past 3 years, the PCOR Partnership has coordinated a regulatory meeting for open discussion among the region's regulatory personnel in an effort to provide updates on the current status and evolving nature of regulations that affect CO_2 capture, compression, transport, and injection for storage and EOR operations for all regional jurisdictions. It is hoped that this will facilitate better coordination for regulatory strategies and, ultimately, enhance opportunities for CO_2 storage and EOR in the PCOR Partnership region.





Cover of the fourth edition of the PCOR Partnership regional atlas.

Southeast Regional Carbon Sequestration Partnership

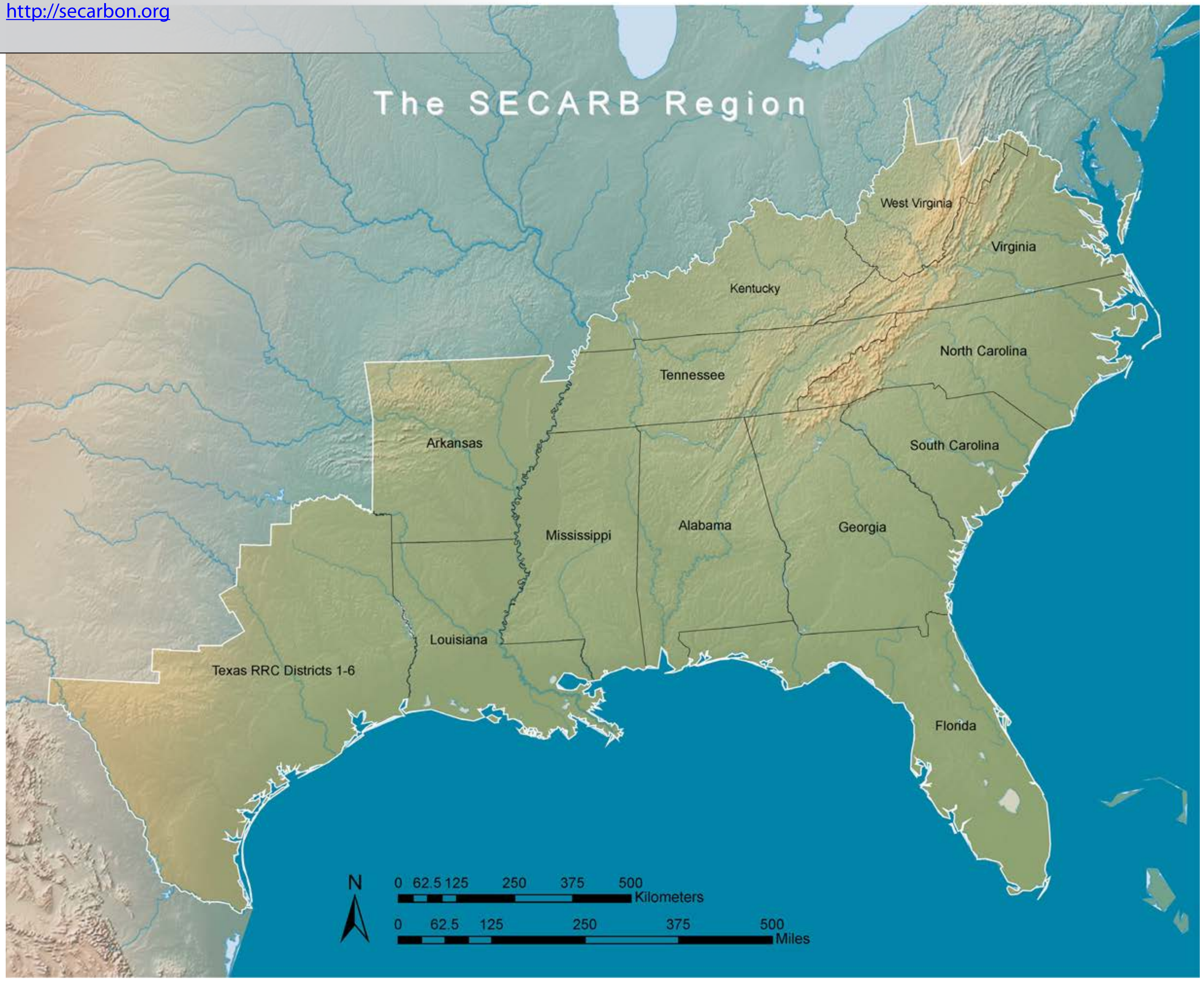
Contact

If you have any questions, comments, or would like more information about SECARB, please contact:

Kenneth J. Nemeth
Southern States Energy Board
Phone: 770-242-7712

http://secarbon.org

SECARB Southeast Regional Carbon Sequestration Partnership



The Southeast Regional Carbon Sequestration Partnership (SECARB), managed by the Southern States Energy Board, represents a 13-state region, including Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, eastern Texas, and Virginia and portions of Kentucky and West Virginia. SECARB comprises more than 100 participants representing Federal and state governments, industry, academia, and nonprofit organizations.

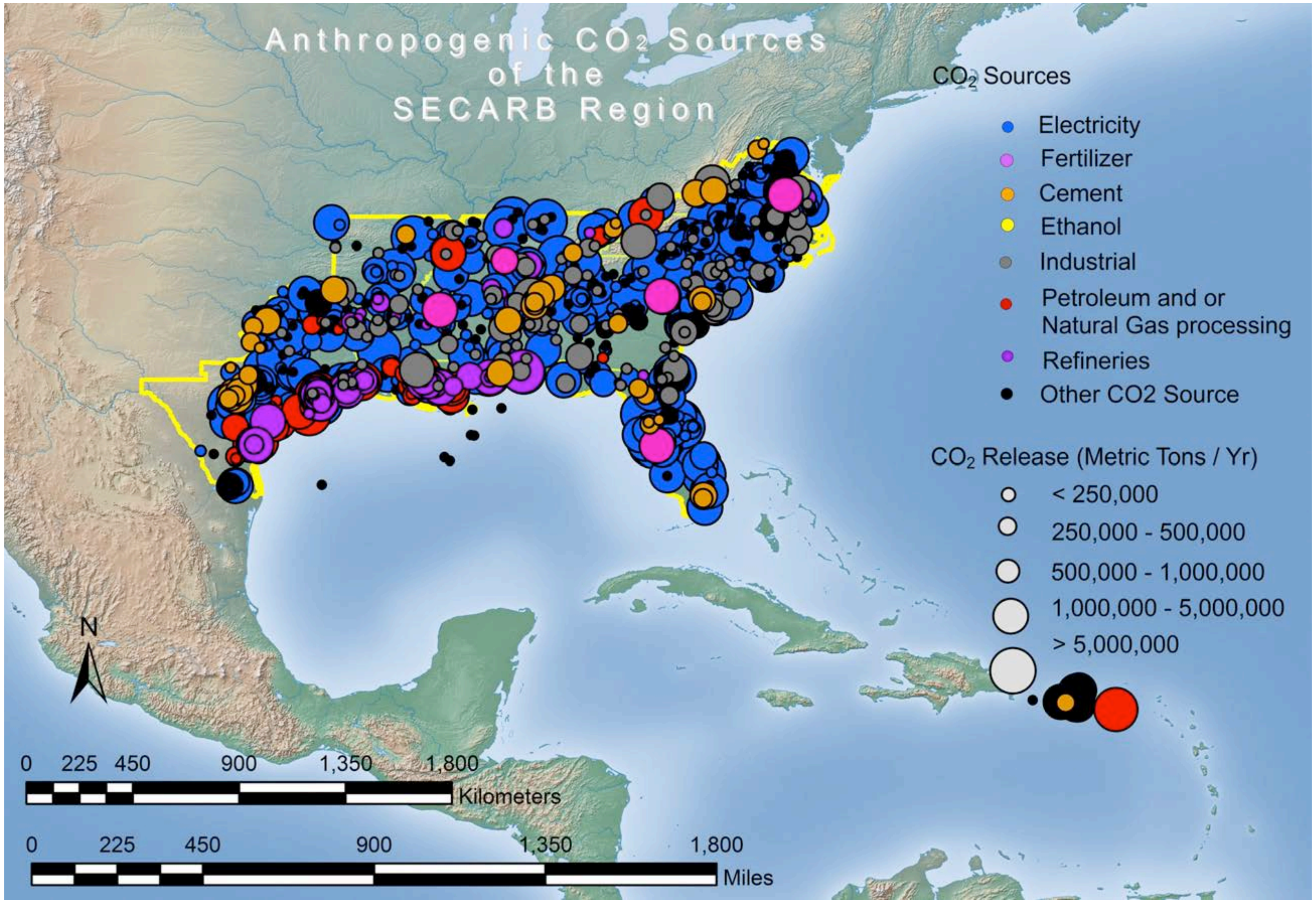
The primary goal of SECARB is to develop the necessary framework and infrastructure to conduct field tests of carbon storage technologies and to evaluate options and potential opportunities for the future commercialization of carbon storage in the region. The SECARB partners are accomplishing this goal by designing and operating six field projects across the region. Four are small-scale projects and two are large-scale projects.

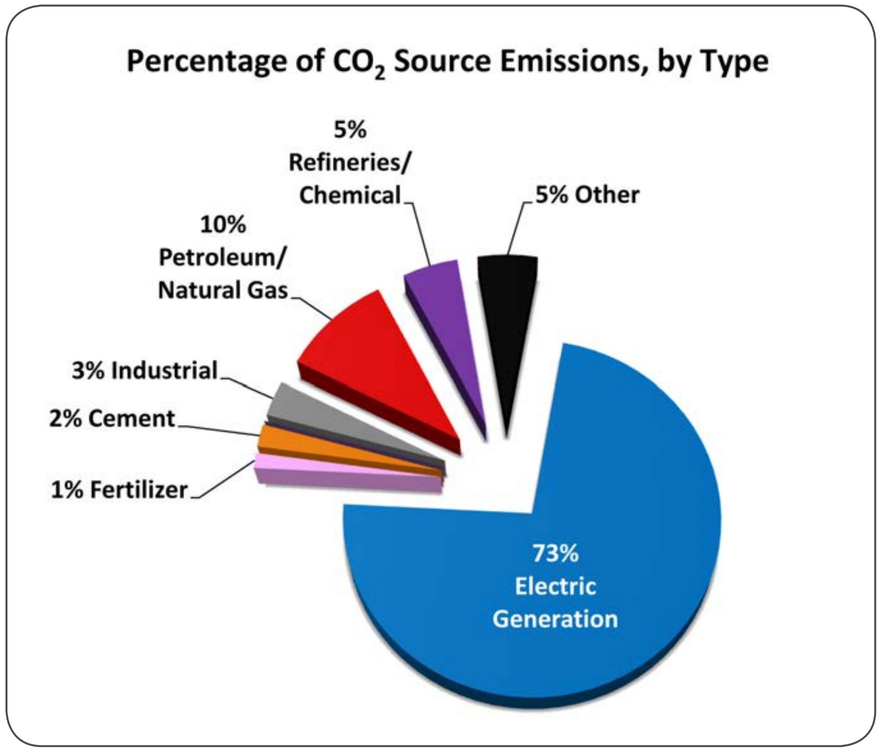
In addition, SECARB continues to characterize the region's geologic storage options, both onshore and offshore; identify barriers and opportunities for the wide-scale construction of pipelines to transport CO_2 for the purposes of storage, EOR, and other commercial uses; monitor Federal and state regulatory and legislative activities; and support local, regional, national, and international education and outreach efforts related to SECARB and the RCSP Program.

SECARB CO_2 Sources

In the SECARB region, there are more than 900 large stationary CO_2 sources, which are targets for future carbon storage projects. Their total annual emissions are estimated at more than 1 billion metric tons (1.2 billion tons) of CO_2. Fossil fuel-fired (coal, oil, or gas) power plants are the largest contributors, accounting for more than 70 percent of the total CO_2 emissions.

The SECARB region also hosts a number of non-power related stationary sources of CO_2. These include, in descending order of contribution of CO_2, refineries/chemical plants, industrial plants, cement plants, and fertilizer plants.

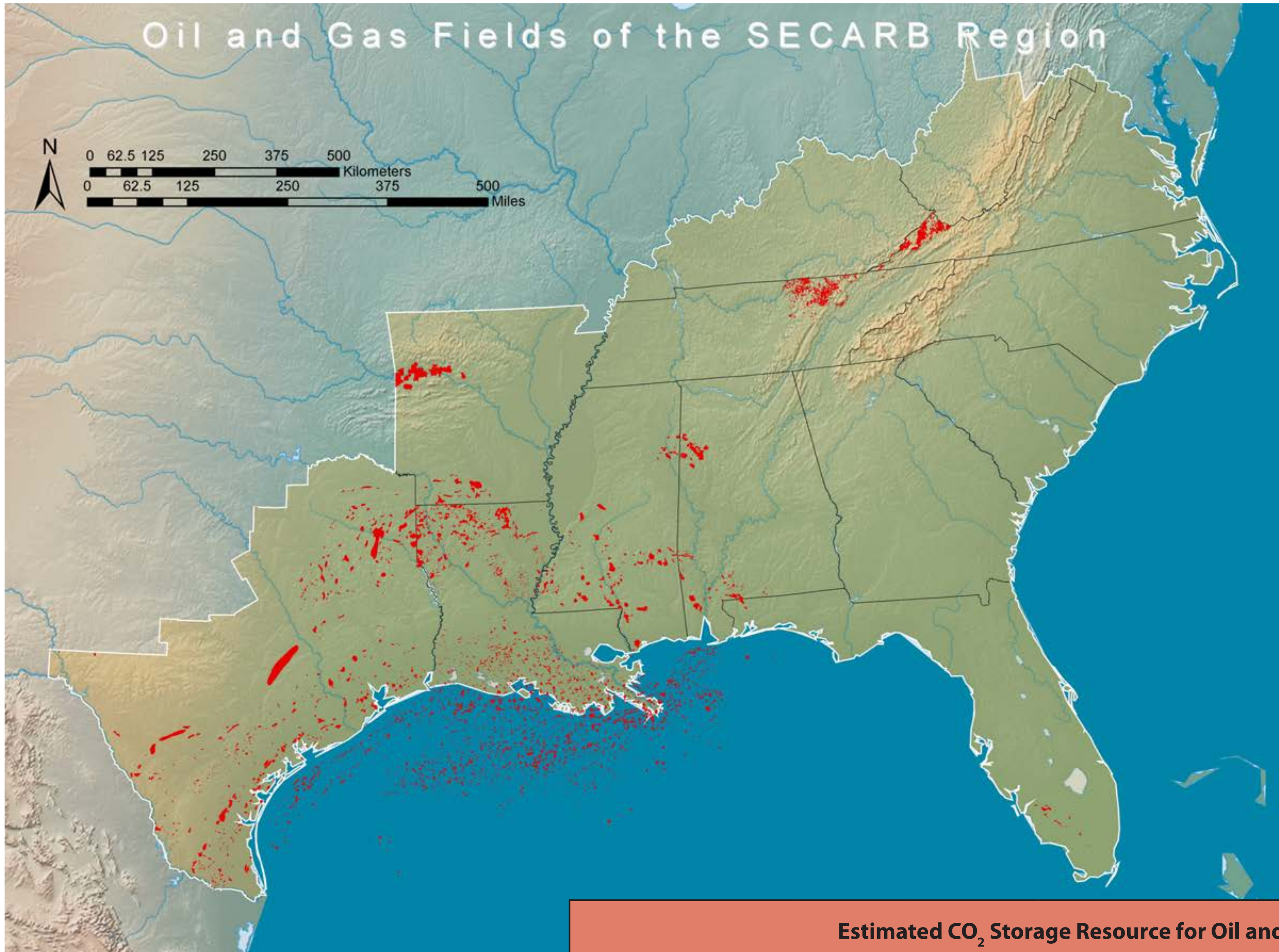




CO_2 Stationary Sources of the SECARB Region (million metric tons of CO_2 per year)									
State	"Electric Generation"	Fertilizer	"Cement Plants"	Ethanol	Industrial	"Petroleum/ Natural Gas"	"Refineries/ Chemical"	Other	Total
AL	77.8	0.6	6.3	0.0	8.8	0.9	1.1	2.7	98.3
AR	33.0	0.0	1.2	0.0	2.2	0.0	0.9	0.7	37.9
FL	122.1	2.0	2.4	0.0	2.2	0.0	5.9	4.9	139.4
GA	79.9	2.0	0.3	0.0	3.4	0.8	0.0	4.1	90.5
LA	50.9	6.5	0.0	0.0	2.9	37.1	20.1	12.4	129.9
MS	28.4	2.7	0.0	0.0	1.0	0.0	5.2	1.1	38.3
NC	68.0	0.0	0.0	0.0	4.0	0.0	0.0	5.1	77.1
SC	41.0	0.0	1.5	0.0	3.8	0.0	0.0	3.1	49.3
TN	42.5	0.0	1.0	0.0	1.3	6.1	0.5	2.0	53.5
TX*	213.1	0.0	8.1	0.0	1.6	62.4	20.0	17.3	322.5
VA	32.0	1.1	1.4	0.0	3.8	0.0	0.0	4.5	42.8
Total	**788.7**	**14.9**	**22.2**	**0.0**	**35.0**	**107.3**	**53.7**	**57.9**	**1,079.7**

SECARB Shares KY and WV with other RCSPs. Data for these States can be found under MGSC and/or MRCSP.

*Eastern Texas, TRRC Districts 1-6.



SECARB Oil and Gas Reservoirs

The SECARB region has a rich history of oil and gas production, particularly in the Gulf Coast states of Alabama, Louisiana, Mississippi and eastern Texas (TRRC Districts 1–6). As such, considerable information exists about the geologic settings and reservoir properties of these potential CO_2 storage sites.

The region has produced nearly 7 billion cubic meters (44 billion barrels) of oil and nearly 9.4 trillion cubic meters (332 trillion cubic feet) of natural gas. Application of CO_2-EOR could add 2.1 billion cubic meters (13 billion barrels) of oil to these totals. These oil and gas reservoirs could provide opportunities for storing CO_2, assuming the water and low pressure hydrocarbons occupying this pore space can be efficiently displaced with injected CO_2.

CO_2-EOR production wellhead. (Photo courtesy of TX BEG)

CO_2-EOR operations. (Photo courtesy of Denbury Resources Inc.)

Estimated CO_2 Storage Resource for Oil and Gas Reservoirs in the SECARB Region

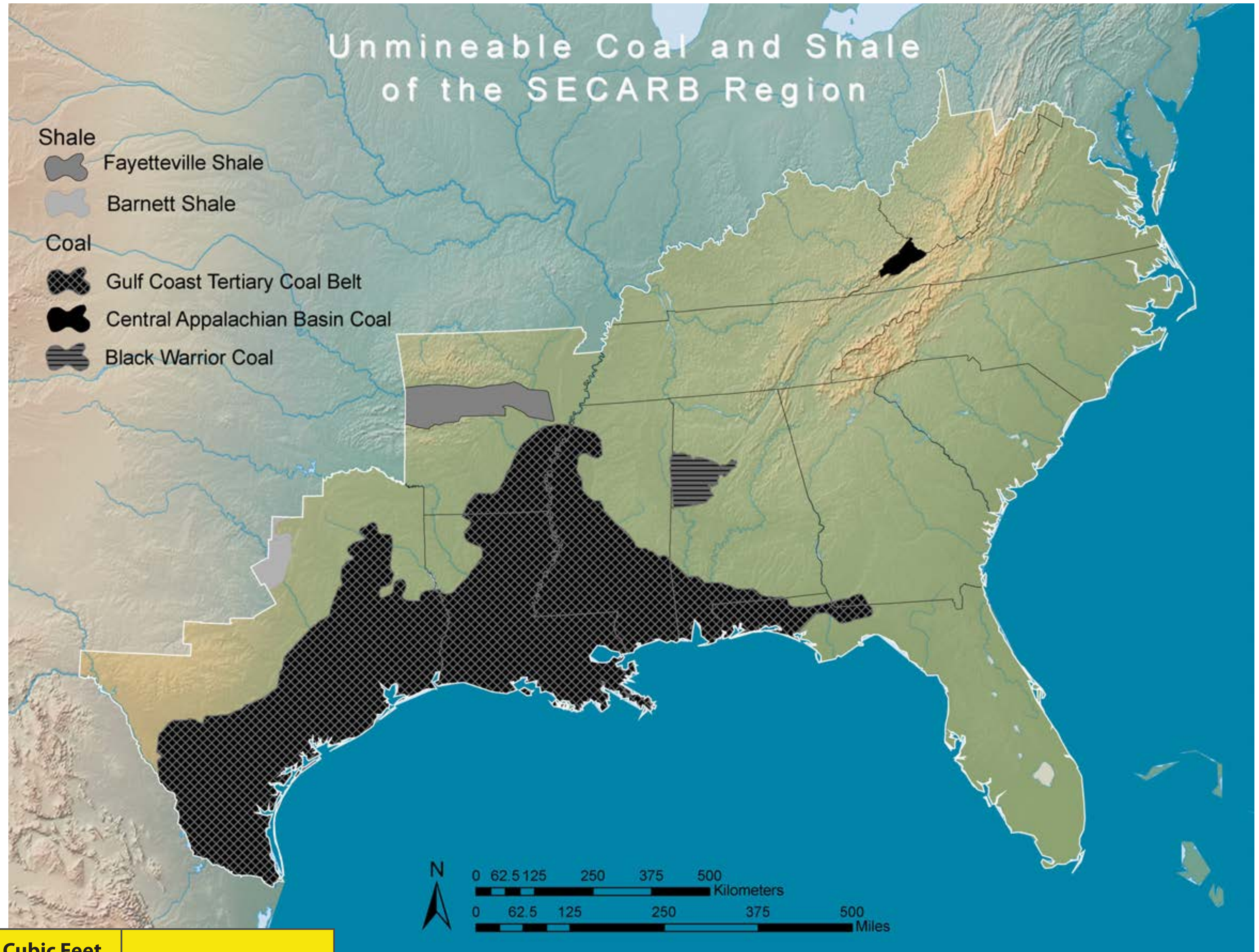
State	Number of Fields		Cumulative Conventional Recovery		Conventional CO_2 Storage Resource		Technically Recoverable Oil from CO_2-EOR	Additional CO_2 Storage Resource*	
	Total	Assessed	Oil Million Bbls	Gas Bcf	Million Metric Tons	Bcf	Million Bbls	Million Metric Tons	Bcf
AL	133	63	622	1,856	344	6,504	410	86	1,640
AR	42	42	1,394	1,415	250	4,728	340	72	1,360
FL	23	8	556	0	109	2,061	180	38	720
LA	964	331	11,847	117,697	6,781	128,153	5,480	1,160	21,920
MS	110	101	1,346	5,300	399	7,549	850	180	3,400
TN	213	213	-	-	-	-	-	-	-
VA	49	49	-	89	10	180	-	-	-
Federal Offshore	1,337	1,001	15,843	176,466	17,754	335,550	5,890**	1,246	23,560
TX***	678	678	12,510	29,373	4,005	75,695	n/a	n/a	n/a
TOTAL	**3,549**	**2,486**	**44,118**	**332,196**	**29,652**	**560,420**	**7,260**	**2,782**	**52,600**

SECARB Shares KY and WV with other RCSPs. Data for these states can be found under MGSC and/or MRCSP.
*Additional storage resource calculated by using 4 Mcf of CO_2 storage per barrel of technically recoverable CO_2-EOR oil.
** CO_2-EOR assessed for offshore shallow water Louisiana fields only.
*** Eastern Texas, TRRC Districts 1-6

SECARB Unmineable Coal

Three significant coal basins and two gas shale basins have been assessed within the SECARB region. The first of the coal basins, the Virginia portion of the Central Appalachian Basin, may have the potential to hold 231 million–982 million metric tons (255–1,082 million tons) of CO_2. The Black Warrior Basin in Alabama and Mississippi has a potential storage resource of 669 million–1,529 million metric tons (737 million–1,685 million tons) of CO_2. The third coal basin, the areally extensive Gulf Coast Tertiary Coal Belt, may have the potential to hold 32 billion–72 billion metric tons (35 billion–80 billion tons) of CO_2.

To date, the SECARB partners have examined two gas shale basins in this region: the Arkoma (Fayetteville) Shale in the Arkoma Basin of Arkansas and the Barnett Shale in Texas. The Arkoma Shale is estimated to have a CO_2 storage resource of 14 billion–20 billion metric tons (16 billion–22 billion tons). The Barnett Shale is estimated to have a CO_2 storage resource of 19 billion–27 billion metric tons (21 billion–30 billion tons). During the SECARB large-scale field project program, the partners quantified other coal and shale basins in the region as potential CO_2 storage options.

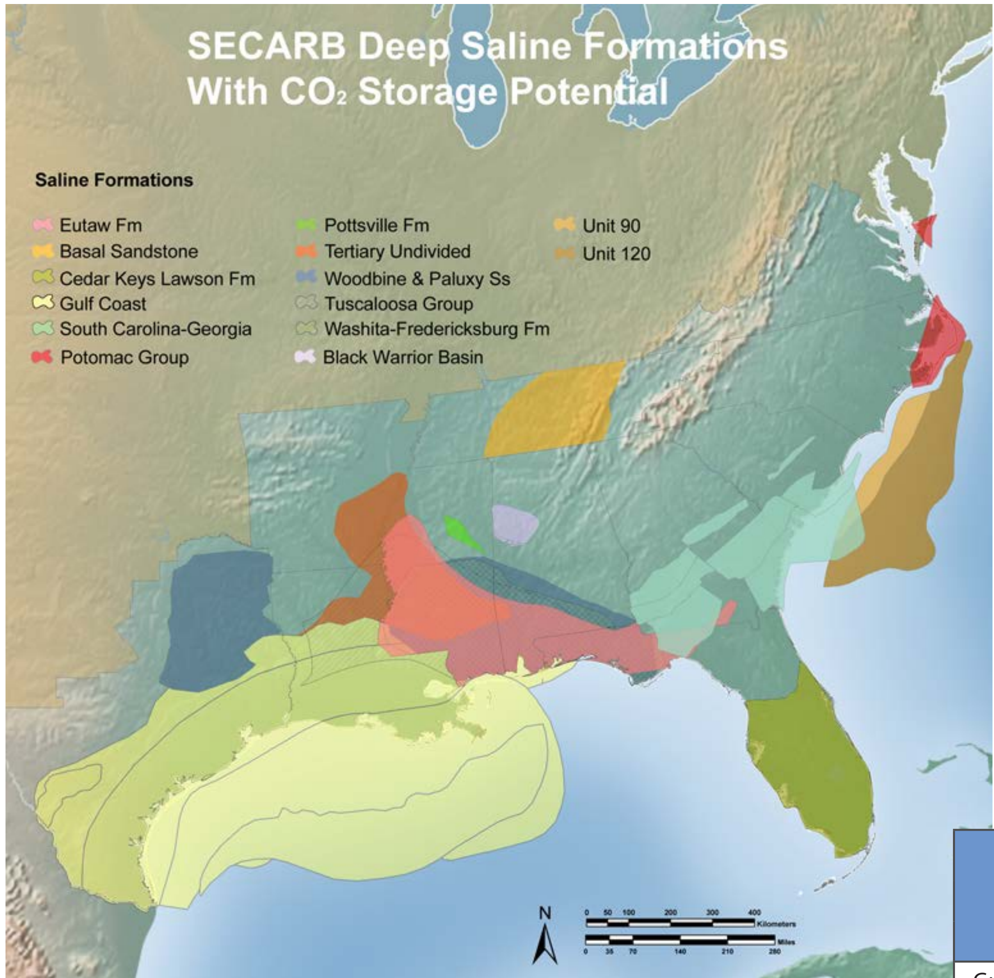


Basin	State	Status of Development	Area (square miles)	Trillion Cubic Feet (Tcf)		Billion Metric Tons	
				Low Estimate	High Estimate	Low Estimate	High Estimate
COAL	VA	Mature	1,269	4	19	0.2	1.0
Central Appalachian	AL	Mature	4,389	13	29	0.7	1.5
Black Warrior	TX*	Undeveloped	71,277	265	606	14.0	32.0
Gulf Coast Tertiary Coal Belt	LA	Undeveloped	40,501	157	358	8.3	19.0
	MS	Undeveloped	28,195	102	234	5.4	12.4
	AR	Undeveloped	7,829	30	69	1.6	3.6
	FL	Undeveloped	6,100	24	55	1.3	2.9
	AL	Undeveloped	5,915	24	55	1.3	2.9
	GA	Undeveloped	501	–	–	–	–
TOTAL COAL			165,976	619	1,425	33	75
SHALE							
Arkoma (Fayetteville)	AR	Emerging	8,610	266	380	14.1	20.1
Barnett	TX*	Emerging	7,902	356	508	19.0	27.0
TOTAL SHALE			16,512	622	888	33	47

SECARB shares KY and WV with other RCSPs. Data for these states can be found under MGSC and/or MRCSP.

* Eastern Texas, TRRC Districts 1-6

Injection operations at the Central Appalachian (left) and the Black Warrior Basin (right) project sites.



SECARB Saline Formations

Much of the CO_2 storage resource of the SECARB region lies in a thick wedge of sandstones in several sub-basins along the Gulf Coast. Sandstones of the Cretaceous Tuscaloosa Formation and the Paluxy Formation host the current SECARB large-scale field projects, providing an opportunity for scientists to further assess regional geology during detailed site characterization efforts. The Cretaceous Eutaw Formation and Washita-Fredericksburg interval are newly assessed. The Paluxy Formation resource estimate has been refined with newly collected data for Mississippi, Alabama, and Florida. The basal sandstones of Tennessee, including the Mt. Simon Formation, also have been refined. Other Cretaceous formations that provide potential storage resource include sandstones in Texas, from South Carolina to Georgia, the subseabed in the Atlantic Ocean offshore of the Carolinas and Virginia, and carbonates and sandstones in Florida. Overlying Tertiary formations extend offshore and offer additional storage potential. The current assessment establishes that the saline formations in the SECARB region have the potential to store approximately 1,376 billion–14,089 billion metric tons (1,517 billion–15,530 billion tons) of CO_2.

In 2011, the Savannah River National Laboratory completed a study entitled Reconnaissance Assessment of the CO_2 Sequestration Potential in the Triassic Age Rift Basin Trend of South Carolina, Georgia, and Northern Florida. They conservatively calculated a storage resource of 137 billion metric tons (151 billion tons). Based upon a revised configuration of the basins using GIS and including previous offshore estimates, the storage resource could be as much as 204 billion-244 billion metric tons (225 billion-269 billion tons). Further investigation is needed to quantify the storage potential.

Saline Formations	State	CO_2 Storage Resource	
		Million Metric Tons	
		Low Estimate	High Estimate
Gulf Coast Basins (Pliocene)	Multiple States*	136,006	1,870,083
Gulf Coast Basins (Miocene)	Multiple States*	401,185	5,516,295
Gulf Coast Basins (Oligocene)	Multiple States*	131,661	1,810,337
Gulf Coast Basins (Eocene)	Multiple States	156,551	2,152,574
Gulf Coast Basins (Tertiary Undivided)	Multiple States	17,065	234,639
Gulf Coast Basins (Olmos)	TX**	446	6,126
Eutaw Formation	Multiple States	22,564	73,179
Tuscaloosa Group	Multiple States	5,433	74,704
Washita-Fredericksburg Interval	Multiple States	225,057	729,913
Woodbine and Paluxy Formations	Multiple States	22,787	643,888
Pottsville Formation	Multiple States	1,299	17,858
Parkwood Formation	AL	20	838
Bangor Limestone	AL	3	44
Floyd Shale	AL	9	119
Tuscumbia and Fort Payne Formations	AL	19	263
Basal Sandstone (Includes Mt. Simon)	TN	407	3,894
Potomac Group	Multiple States*	1,778	24,453
South Carolina, Georgia, North Florida Basins	Multiple States*	203,753	244,248
Cedar Keys, Lawson Formations	FL	11,104	152,680
Offshore Atlantic (Unit 120)	Federal Offshore	35,624	489,830
Offshore Atlantic (Unit 90)	Federal Offshore	3,104	42,680
TOTAL*		**1,375,874**	**14,088,646**

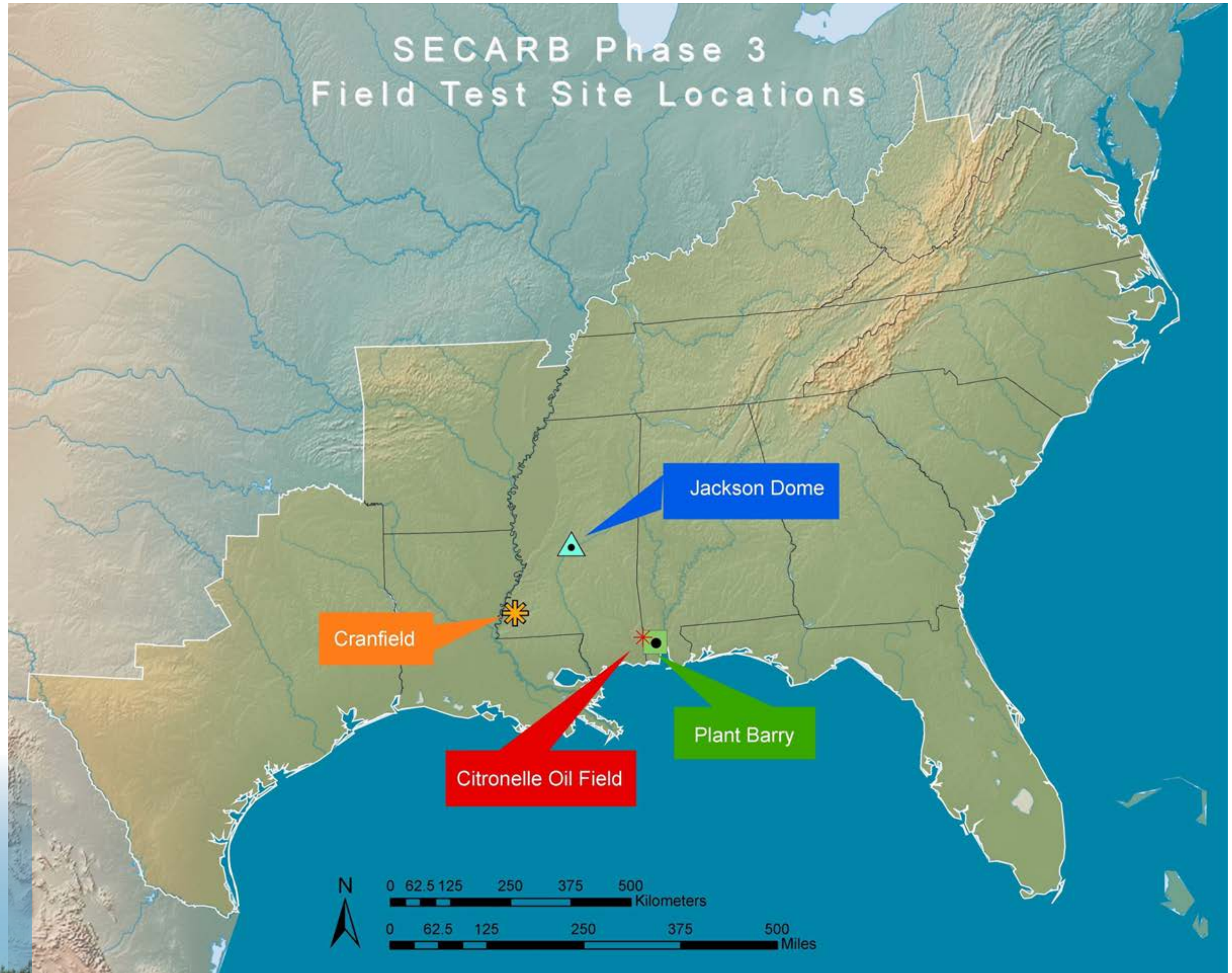
SECARB shares KY and WV with other RCSPs. Data for these states can be found under MGSC and/or MRCSP.
* Including offshore Federal Waters
** Eastern Texas, TRRC Districts 1-6

SECARB Large-Scale Projects

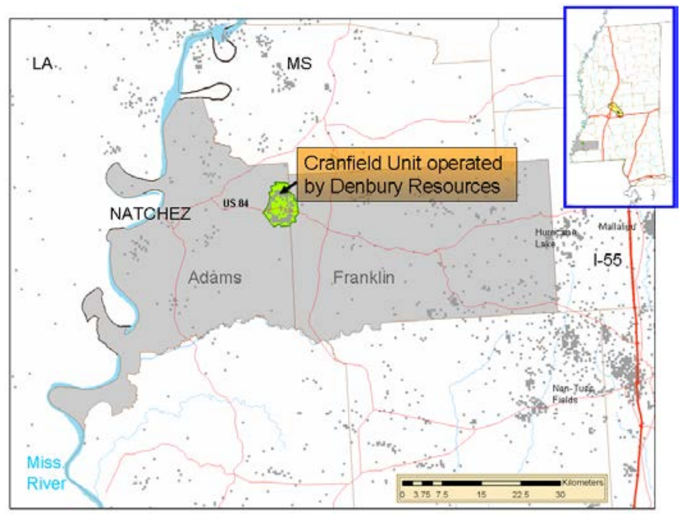
Two SECARB large-scale projects are underway in the Southeast: the Early Test and the Anthropogenic Test.

Early Test

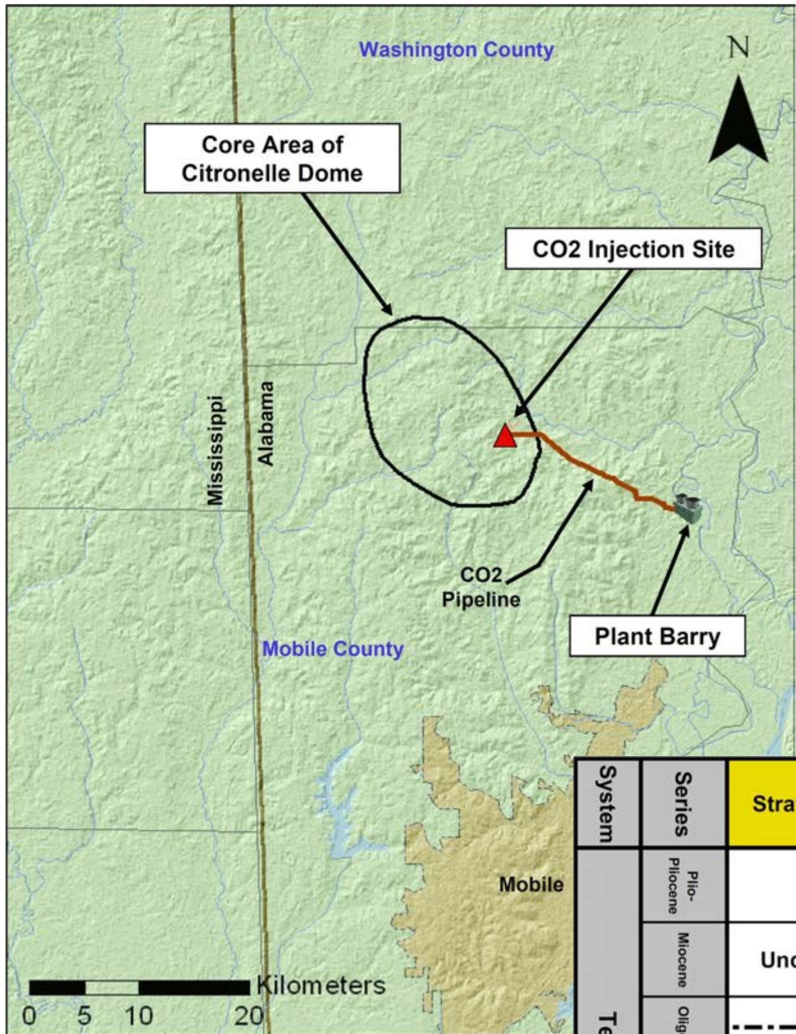
In July 2008, Denbury Onshore, LLC, began CO_2-EOR operations at the Cranfield oil field located east of Natchez, Mississippi. The SECARB Early Test team, led by the Gulf Coast Carbon Center at the Bureau of Economic Geology at The University of Texas at Austin, takes advantage of the ongoing CO_2-EOR efforts by Denbury to field test a variety of MVA technologies and to collect continuous data for long-term CCUS analysis. In August 2009, the team met a milestone of monitoring an injection of more than 1 million tonnes of CO_2. In November 2009, DOE recognized the SECARB Early Test for furthering CCUS technology and meeting a G-8 goal for the deployment of 20 similar projects by 2010. The Early Test is the fifth project worldwide to reach this CO_2 injection volume and the first in the United States. As of June 2012, the project team has monitored the injection and storage of more than 3.8 million metric tons (4.2 million tons) of CO_2 at this site.



Early Test monitoring well and Detailed Area of Study. (Photos courtesy of SSEB)



Map identifying the location of the Early Test near Natchez, Mississippi. (Image courtesy of TX BEG)



Map identifying the location of the CO_2 capture facility at Plant Barry, the pipeline route, and the Citronelle domal structure at the oil field.

CO_2 capture facility at Plant Barry. (Photo courtesy of Southern Company)

SECARB Large-Scale Projects

Anthropogenic Test

The SECARB large-scale Anthropogenic Test is a fully integrated CO_2 capture, transportation, and geologic storage project. Under separate funding, CO_2 is captured at Alabama Power Company's James M. Barry Electric Generating Plant (Plant Barry), a coal-fired facility located in Bucks, Alabama. The CO_2 is transported via a newly constructed 12-mile pipeline to the Citronelle oil field near Citronelle, Alabama, both operated by Denbury Onshore, LLC. The CO_2 is injected and stored within the saline Paluxy Formation at a depth of 9,400 feet. During the project, Denbury will inject approximately 100,000 tonnes of CO_2 per year for up to 3 years. Based upon lessons learned at the Early Test and the experimental nature of the project, the SECARB team is deploying an extensive MVA program throughout the project life cycle (pre-, during, and post-injection). The Anthropogenic Test is the first RCSP large-scale project to utilize anthropogenic CO_2 from a coal-fired power facility for geologic storage. The Electric Power Research Institute leads the capture project.

System	Series	Stratigraphic Unit	Major Sub Units	Potential Reservoirs and Confining Zones
Tertiary	Plio-Pliocene		Citronelle Formation	Freshwater Aquifer
Tertiary	Miocene	Undifferentiated		Freshwater Aquifer
Tertiary	Oligocene		Chickasawhay Fm.	Base of USDW
Tertiary	Oligocene	Vicksburg Group	Bucatunna Clay	Local Confining Unit
Tertiary	Eocene	Jackson Group		Minor Saline Reservoir
Tertiary	Eocene	Claiborne Group	Talahatta Fm.	Saline Reservoir
Tertiary	Paleocene	Wilcox Group	Hatchetigbee Sand Bashi Marl Salt Mountain LS	Saline Reservoir
Tertiary	Paleocene	Midway Group	Porters Creek Clay	Confining Unit
Cretaceous	Upper	Selma Group		Confining Unit
Cretaceous	Upper	Eutaw Formation		Minor Saline Reservoir
Cretaceous	Upper	Tuscaloosa Group	Upper Tusc.	Minor Saline Reservoir
Cretaceous	Upper	Tuscaloosa Group	Mid. Tusc. Marine Shale	Confining Unit
Cretaceous	Upper	Tuscaloosa Group	Lower Tusc. Pilot Sand Massive sand	Saline Reservoir
Cretaceous	Lower	Washita-Fredericksburg	Dantzler sand	Saline Reservoir
Cretaceous	Lower	Washita-Fredericksburg	Basal Shale	Primary Confining Unit
Cretaceous	Lower	Paluxy Formation	'Upper' 'Middle' 'Lower'	Injection Zone
Cretaceous	Lower	Mooringsport Formation		Confining Unit
Cretaceous	Lower	Ferry Lake Anhydrite		Confining Unit
Cretaceous	Lower	Donovan Sand	Rodessa Fm. Upper' 'Middle' 'Lower'	Oil Reservoir Minor Saline Reservoir Oil Reservoir

The stratigraphic column at right identifies regional saline reservoirs and confining units. The Paluxy Formation is the target reservoir for CO_2 injection and storage. (Images courtesy of Advanced Resources International, Inc.)

Dedicated CO_2 pipeline extends 12 miles from Plant Barry to the Citronelle oil field. (Photo courtesy of Denbury Resources Inc.)

CO_2 injection well at Denbury's Citronelle oil field. (Photo courtesy of SSEB)

Commercialization in the SECARB Region

Early opportunities for commercialization in the SECARB region most likely will be associated with offsetting the cost of capturing and storing CO_2. Utilizing CO_2-EOR is the primary candidate to offset costs in several SECARB states. SECARB's in Gulf Coast formations will assist in expanding CO_2-EOR opportunities. Another candidate is ECBM recovery utilizing CO_2. SECARB's small-scale field projects in Central Appalachia and in the Black Warrior Basin of Alabama will assist in determining the technical and economic feasibility of ECBM recovery.

Within the SECARB region, CO_2-EOR is in place in Texas, Louisiana, and Mississippi. CO_2 that is used for EOR is coming from the Jackson Dome, a natural source of CO_2 located near Jackson, Mississippi. Denbury Resources operates a pipeline network that transports Jackson Dome CO_2 to oil fields in the Southeast. Denbury is establishing agreements with sources of CO_2 that can supplement the volumes of CO_2 produced at Jackson Dome. As a result, the Denbury pipeline system has the potential for becoming the regional backbone of an integrated source-sink network for CO_2.

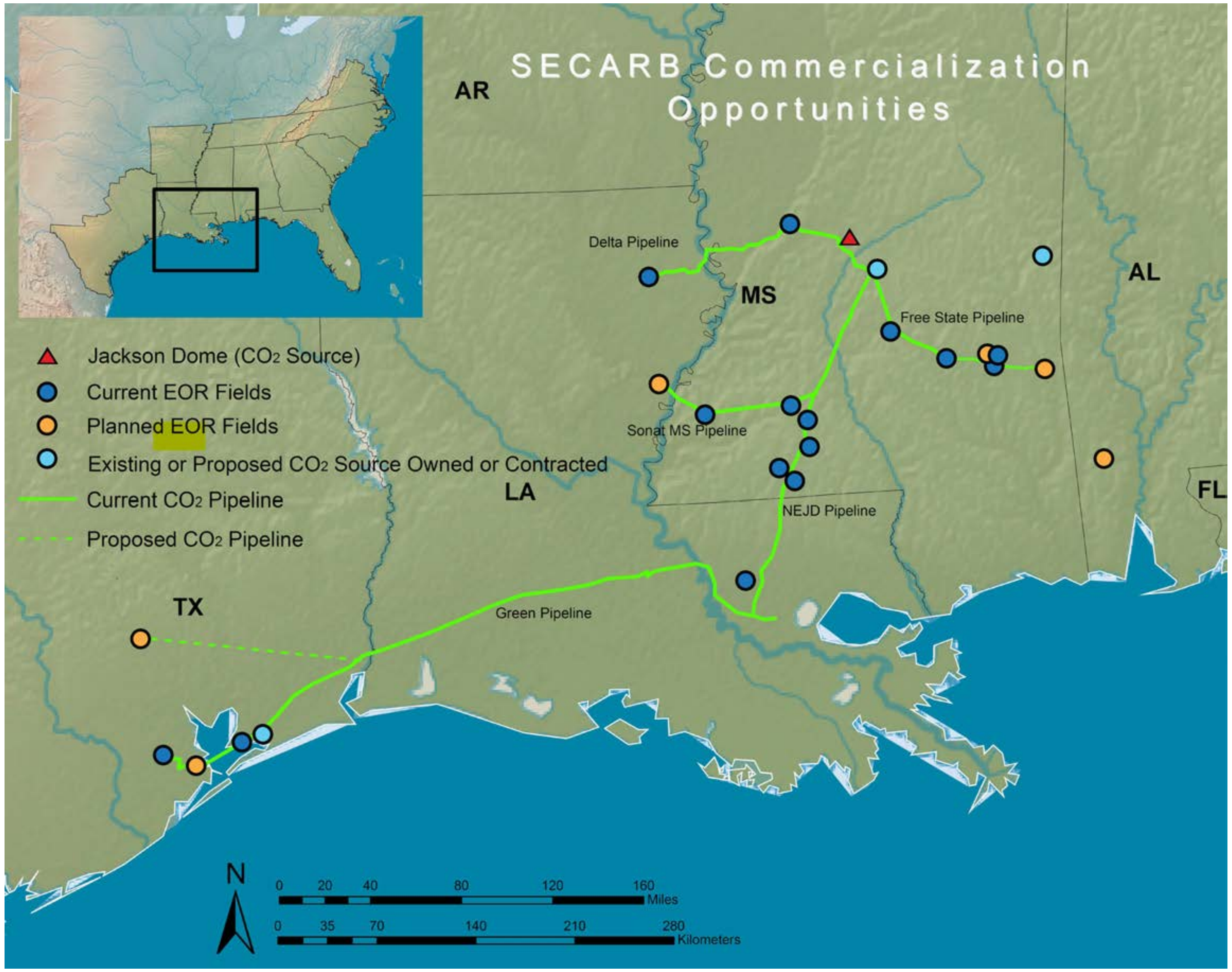
Regional Incentives

Three initiatives in the SECARB region will help advance CCUS deployment:

As part of a SECARB small-scale field investigation, Virginia Tech, Marshall Miller & Associates, and the Geological Survey of Alabama evaluated the feasibility of capturing CO_2 from an industrial source and storing it in unmineable coal seams and associated saline formations in Central Appalachia and the Black Warrior Basin.

Under the SECARB large-scale activities, the Bureau of Economic Geology at The University of Texas at Austin is conducting a large-scale MVA project at Denbury's Cranfield unit near Natchez, Mississippi, where CO_2-EOR began in July 2008. As of June 2012, more than 3.8 million metric tons (4.2 million tons) of CO_2 has been stored.

As part of a SECARB large-scale activities field investigation, the Electric Power Research Institute and Southern Company (with operating units in Mississippi, Alabama, Georgia, and Florida) are currently evaluating CO_2 capture and separation technologies. The SECARB team plans to monitor the injection of 100,000 metric tons per year of anthropogenic CO_2 for up to 3 years.



Jackson Dome (above) and CO_2-EOR operations (right).
(Photos courtesy of Denbury Resources Inc.)

Open house at the SECARB Early Test detailed area of study for national visitors (April 2010).

Open house events at the SECARB Anthropogenic Test capture unit and CO_2 storage sites in Alabama for regional stakeholders in March 2012 (below) and for international visitors representing six countries in May 2012 (right).

Integrating CCUS into the SECARB Community

Outreach and education are key components of success for all three phases of the SECARB program. Conducting effective public outreach involves listening, sharing information, addressing concerns, and communicating project risks early and often. During characterization activities, an action plan for outreach and education related to small-scale CO_2 storage field projects was developed. This action plan has been carried out in the small-scale demonstrations and large-scale projects, which includes the Southern States Energy Board leading the international, national, and regional effort and the individual field teams leading site-specific public outreach activities. Each field site has hosted one or more open house meetings to engage the local community and future CCUS workforce. Knowledge sharing events have been hosted, presentations have been delivered, and posters have been displayed since the SECARB program began in 2003 to share the details of SECARB projects' definitions, designs, implementation, operation, and closeout activities with various audiences. The Southern States Energy Board maintains a website at secarbon.org with current fact sheets, photos of field activities, news, and upcoming and recent events. Timely updates on project activities are communicated through multiple electronic sources, including social networking.

The overall guiding principles of the SECARB outreach and education program are as follows:

- Educate the individuals who will take responsibility for implementing site-specific education and outreach programs
- Present the RCSP and SECARB programs to various audiences
- Develop education and outreach action plans
- Identify the materials and support needed to implement these plans

SECARB Risk Management and Environmental Protection Activities

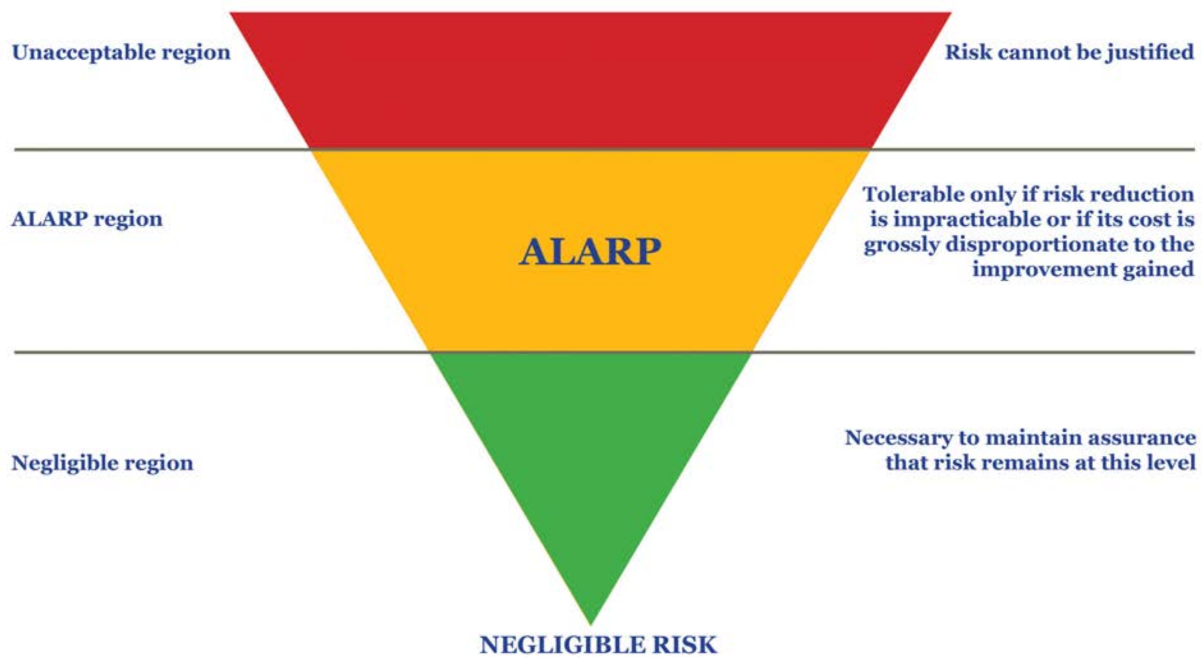
Risk management and environmental protection are central concerns in any CCUS project to ensure human health and safety. Operational risks must be identified, assessed for consequence and likelihood, documented early, and revisited often to safeguard the environment. As commercial-scale CCUS projects are initiated, it is important to understand the complexities that exist in deploying a fully integrated system. In a commercial setting, there could be multiple owners and operators involved in the entire value chain (CO_2 capture; transport by pipeline; storage; MVA; etc.).

In the case of the SECARB large-scale Anthropogenic Test, the CO_2 capture unit supplying the CO_2 for the project is owned and operated by Alabama Power, a subsidiary of Southern Company. Denbury Onshore, LLC, constructed the pipeline and operates the CO_2 injection well. The SECARB team developed and will operate the MVA program under the direction of the Southern States Energy Board. A framework of legal agreements exists between the three entities to ensure that responsibilities and expectations are clearly defined. The three entities worked cooperatively with Det Norske Veritas to develop a site-specific registry of communication and project-related risks.

Risks associated with the SECARB Anthropogenic Test fall within five primary categories: health and safety, environmental protection, cost, reputation, and schedule to start up integrated operations. These risks are assessed as either slight, minor, moderate, severe, or persistent severe. The goal is to have risk treatment actions in place to reduce the severity to as low as reasonably possible. No risks have been assessed as unacceptable, and the highest risks are related to regulatory uncertainty and successful integration of project components.

	CONSEQUENCE				LIKELIHOOD				
					A: Remote	B: Unlikely	C: Possible	D: Probable	A: Certain
CONSEQUENCE SEVERITY	Health and safety (HS) And Environmental protection (E)	Cost	Reputation	Schedule to start-up of operations	Very unlikely (P<0.05) to occur during life of project	Unlikely to occur during life of project	50/50 chance of occurring during life of project	Likely to occur during life of project	Very likely (P>0.95) to occur during life of project
E: Persistent Severe	HS: On site & off site exposures/injuries. E: Persistent severe damage, Extensive remediation required. Environment restored > 5 years.	More than $10 million	National or International media attention. Regulators shut down operations.	More than 12 months	M	M	H	H	H
D: Severe	HS: On site injuries/exposures leading to absence from work more than 5 days or long term negative health effects. E: Severe environmental damage. Remediation measures required. Environment restored < 5 years	$1 to $10 million	Regional media attention. Regulatory or legal action taken	6-12 months	L	M	M	H	H
C: Moderate	HS: Lost time event/on site injury leading to absence from work up to 5 days, or affecting daily life activities more than five days. E: Damage managed by Company response teams, env. restored < 2 years.	$100 to $1000 k	Local media attention. Regulatory or legal action likely	3-6 months	L	L	M	M	H
B: Minor	HS: Minor injury or health effect - affecting work performance, such as restricting work activities, or affecting daily life activities for up to 5 days. E: Damage, but no lasting effect.	$10 to $100 k	Public awareness may exist, but there is no public concern	1-3 months	L	L	L	M	M
A: Slight	HS: Slight injury or health effect - not affecting work performance or daily life activities. E: Damage contained within premises.	Less than $10 k	On-site communications	Less than 1 month	L	L	L	L	M

The Project Risk Assessment Matrix (HS – health and safety, E – environment, L – low risk, M – medium risk, H – high risk). Colors are indicative of risk level. Risk scenarios in the green band are considered acceptable, those in the red band are currently unacceptable and must be reduced, and risks in the yellow band are of concern but may be tolerable without further risk reduction. (Source: DNV, 2012)



Southwest Regional Partnership on Carbon Sequestration

The Southwest Regional Partnership on Carbon Sequestration (SWP) is investigating the CO_2 storage potential of the abundant oil and gas reservoirs, unmineable coal, and saline formations within the southwestern United States. In 2010, field-scale pilot injection tests were completed, paving the way for larger scale commercial projects, including an EOR project in Texas using an anthropogenic source of CO_2.

SWP draws on the experience of professionals within the fields of geology, engineering, economics, public policy, public outreach, and education. Stakeholders in SWP projects include private industry, non-government organizations, government entities, and, most importantly, the general public. Coordinating SWP is the New Mexico Institute of Mining and Technology, which includes New Mexico, Colorado, Kansas, Oklahoma, Utah, and portions of Arizona, Texas, and Wyoming. To date, field sites for the region are located in New Mexico (San Juan Basin), Utah (Paradox Basin), and Texas (Permian Basin).

Geologic structure in the Southwestern United States.

Contact

If you have any questions, comments, or would like more information aboutt SWP, please contact:

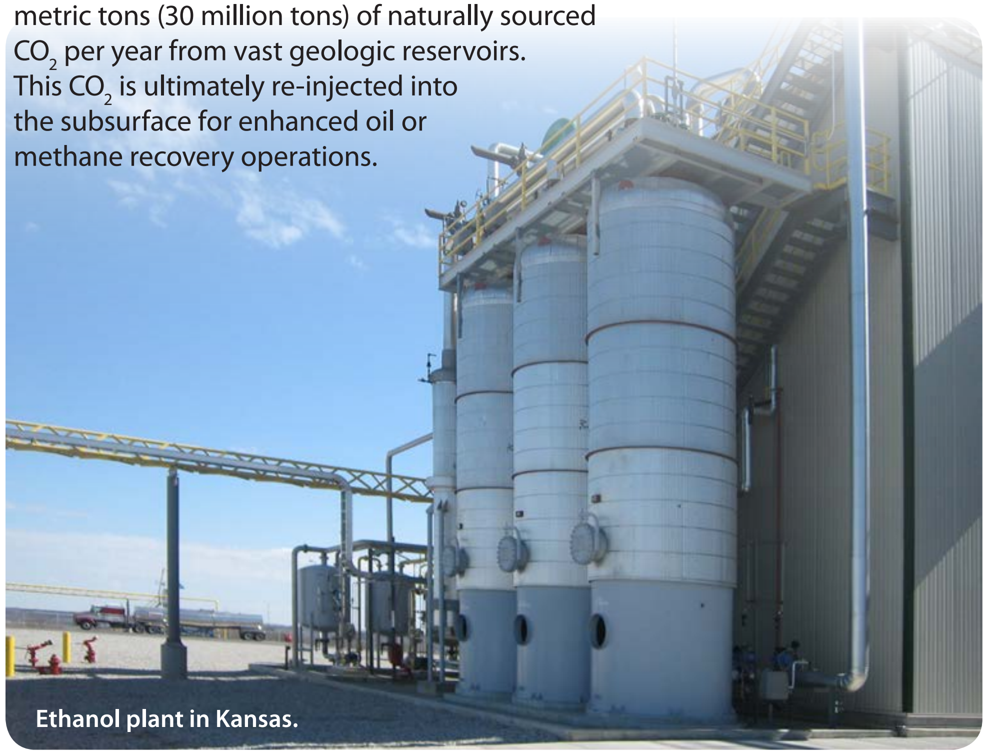
Dr. Reid Grigg
New Mexico Tech

Dr. Brian McPherson
University of Utah

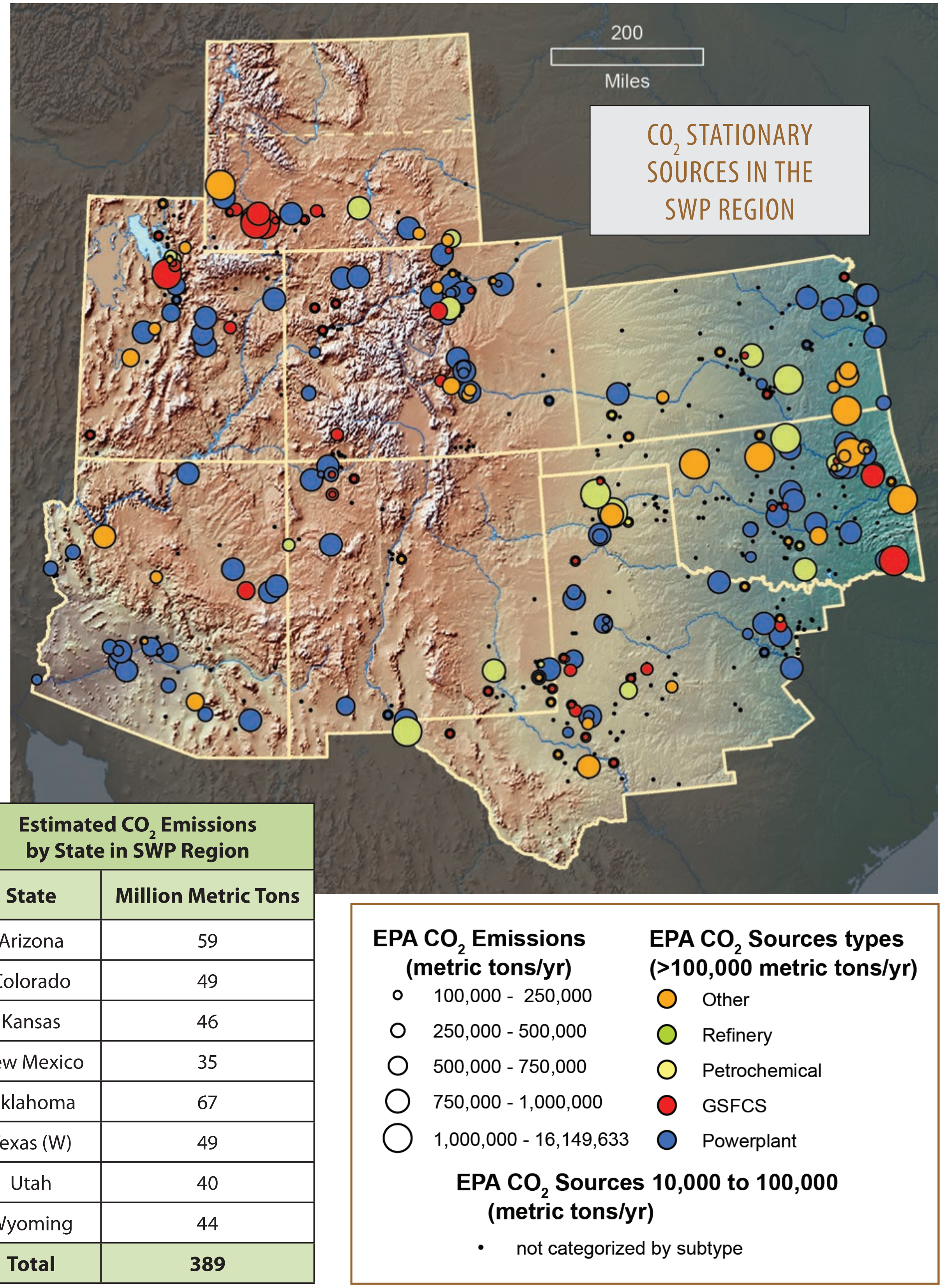
http://southwestcarbonpartnership.org/

SWP CO_2 Sources

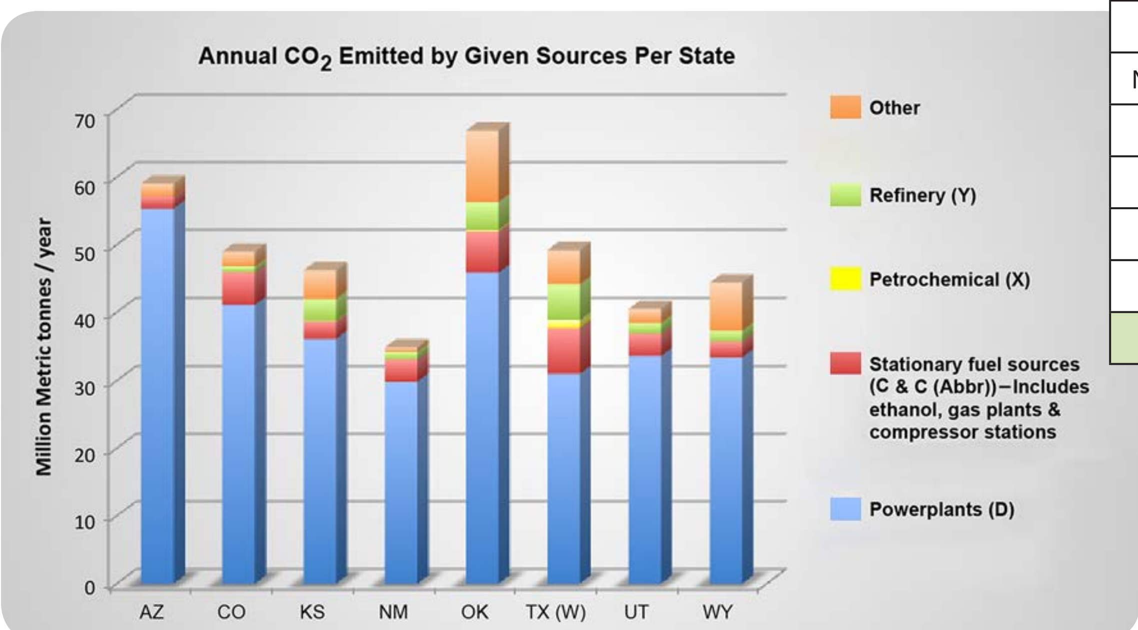
The SWP region contains plentiful supplies of oil, natural gas, and coal. Combustion of these fuels for electricity, transportation, and other industrial processes, produces CO_2. The 10 largest coal-fired power plants in the SWP region emit 125 million metric tons (138 million tons) of CO_2 per year, approaching half of the total emissions of the region. In addition to electrical plants and other stationary sources of anthropogenic CO_2 (natural gas processing plants, refineries, ammonia/fertilizer plants, ethylene and ethanol plants, and cement plants), the SWP region produces and transports more than 27 million metric tons (30 million tons) of naturally sourced CO_2 per year from vast geologic reservoirs. This CO_2 is ultimately re-injected into the subsurface for enhanced oil or methane recovery operations.

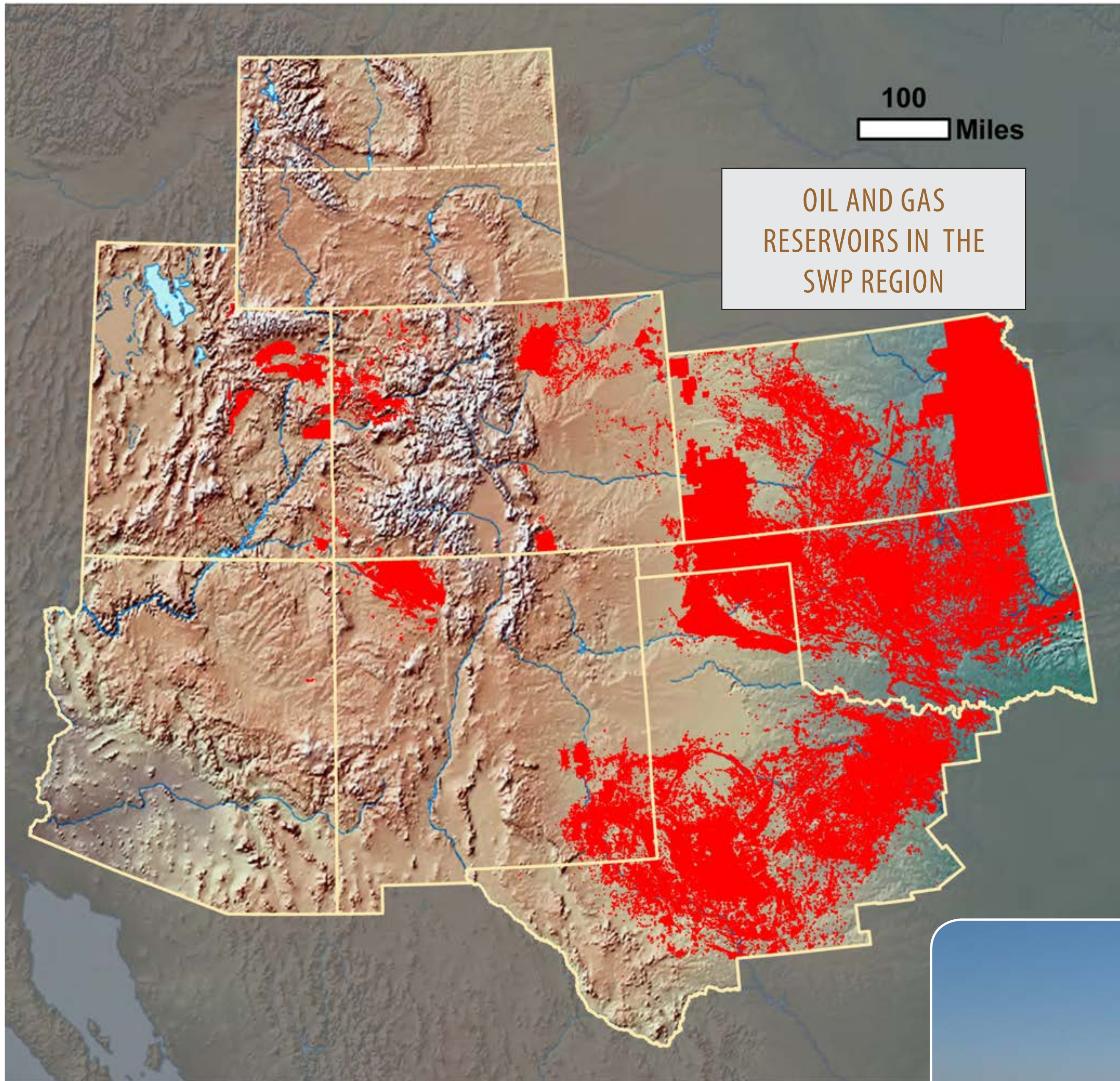


Ethanol plant in Kansas.



Estimated CO_2 Emissions by State in SWP Region	
State	**Million Metric Tons**
Arizona	59
Colorado	49
Kansas	46
New Mexico	35
Oklahoma	67
Texas (W)	49
Utah	40
Wyoming	44
Total	**389**





SWP Oil and Gas Reservoirs

The complex geologic history of the Southwestern United States formed thick stratigraphic sequences that are sources and traps for significant hydrocarbon reserves. Since the early 1900s, oil and gas have been extensively produced from these reservoirs. While oil and gas production remains steady in the region, many areas are starting to transition to secondary and tertiary production that utilizes water and CO_2, respectively, to drive additional oil and gas from the rock. This enhanced petroleum recovery provides an excellent opportunity to utilize the region's CO_2 sources.

Estimated CO_2 Storage Resource in Oil and Gas Reservoirs by State in SWP Region	
State	Million Metric Tons
Arizona	17
Colorado	3,756
Kansas	1,247
New Mexico	9,711
Oklahoma	37,310
Texas	94,305
Utah	2,980

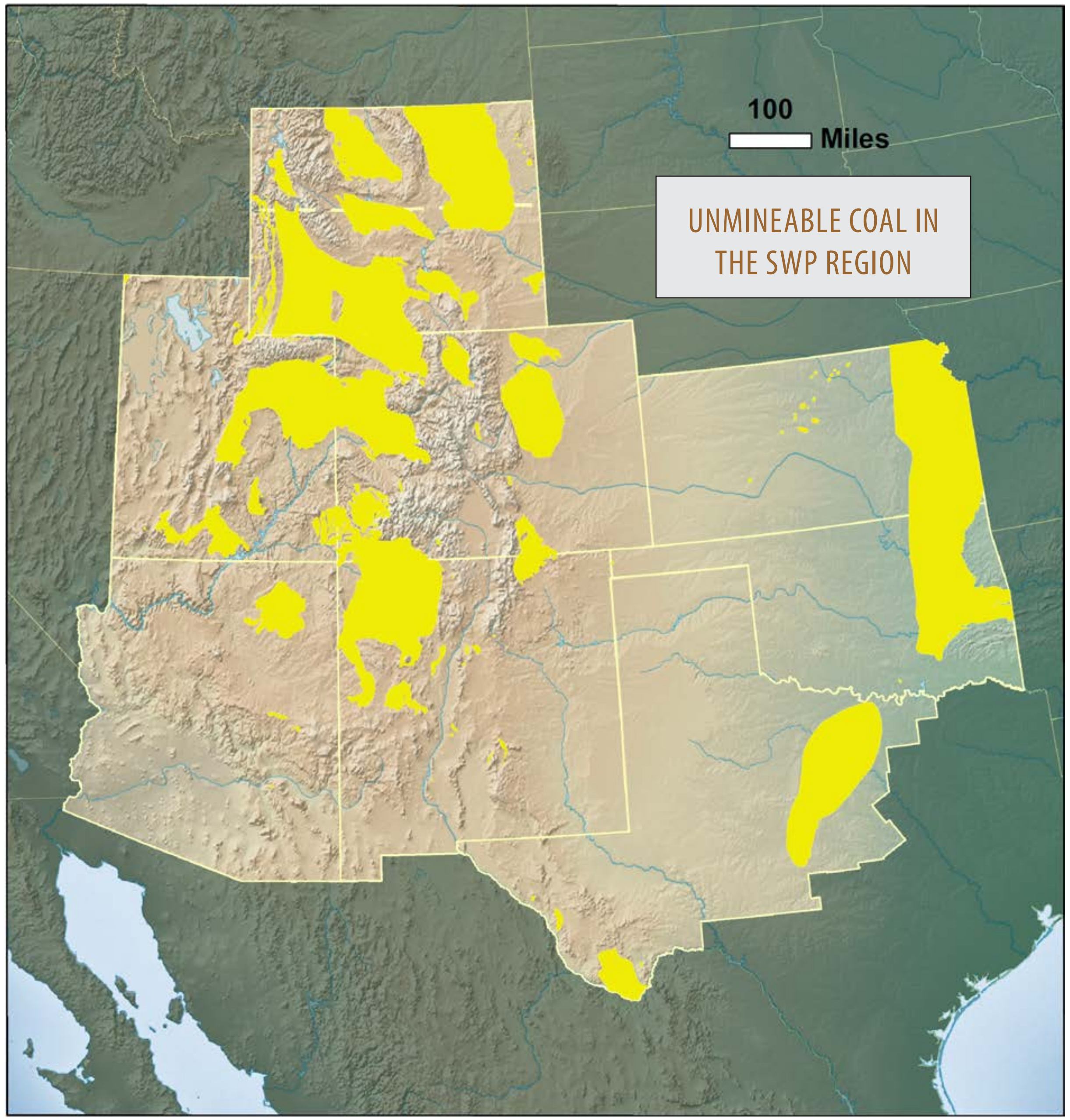
Pump jack at the Aneth oil field, Utah.
(Courtesy of Resolute Energy)

SWP Unmineable Coal

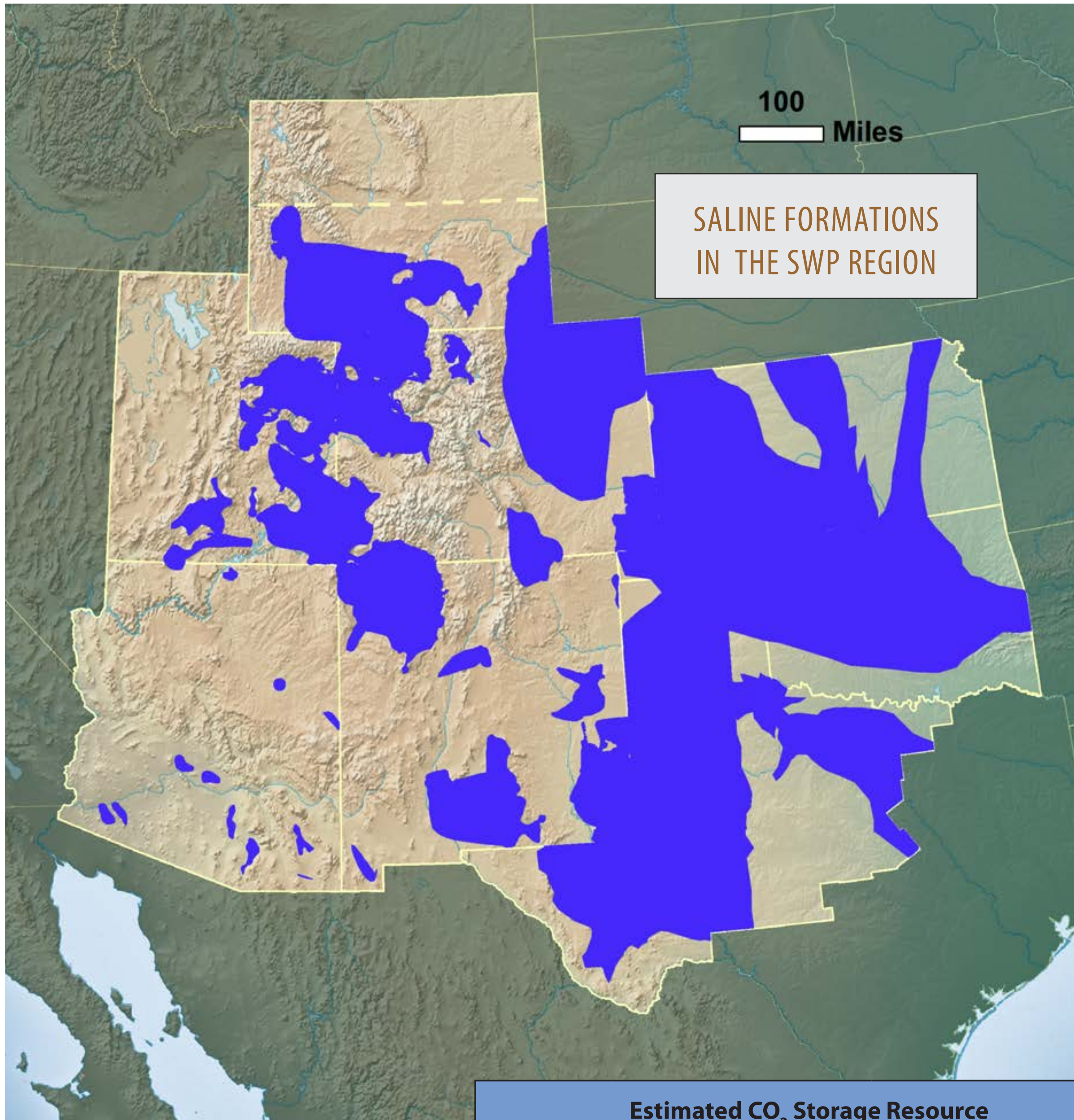
The Southwest United States possesses many significant coal deposits, such as the Cretaceous Fruitland Formation in the SWP region. The Fruitland Formation contains more than 209 billion metric tons (230 billion tons) of coal and is the major coal source in the San Juan Basin of New Mexico and Colorado.

Coal formations that are too deep, too thin, discontinuous, or of poor quality are considered unmineable by technical or economic standards. These unmineable coal seams are common in the SWP region and may yield significant CO_2 storage possibilities.

Many subsurface coal seams are potential storage opportunities.



Estimated CO_2 Storage Resource in Unmineable Coal by State in SWP Region		
State	Low Estimate (million metric tons)	High Estimate (million metric tons)
Arizona	9	37
Colorado	1	2
Kansas	495	882
New Mexico	2	9
Oklahoma	78	312
Utah	2	8
Wyoming	33	133

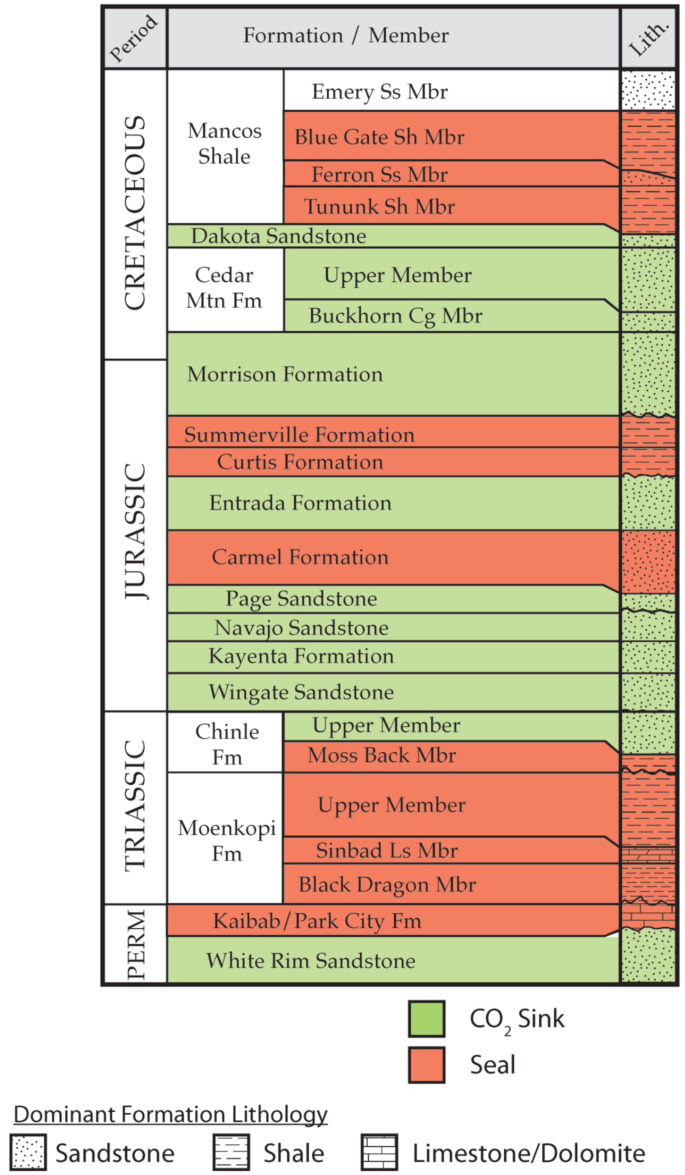


Estimated CO_2 Storage Resource in Saline Formations by State in SWP Region		
State	**Low Estimate (million metric tons)**	**High Estimate (million metric tons)**
Arizona	182	1,931
Colorado	35,805	378,851
Kansas	10,123	89,575
New Mexico	35,446	375,308
Oklahoma	19,419	205,609
Texas	113,850	1,205,467
Utah	23,861	252,641
Wyoming	31,842	337,174

SWP Saline Formations

Multiple interlayered saline formations with corresponding impermeable seals are common, widespread, and represent the majority of the CO_2 storage resource in the SWP region. These sequences, also called stacked saline formation systems, typically range from many thousands to tens of thousands of feet thick.

In Utah and Colorado, two of these stacked sequences are Jurassic- and Cretaceous-aged rock strata, exceeding 2 miles in thickness. These sections were deposited at a time when extensive coastal dunes covered much of the region, followed by rising inland seas. These sandstone deposits typically possess excellent (high) porosity and permeability. The sandstones, in turn, are overlain by tidal flat mudstones, salt layers, and marine carbonates. These formations typically exhibit low porosity and permeability and serve as barriers to CO_2 migration.

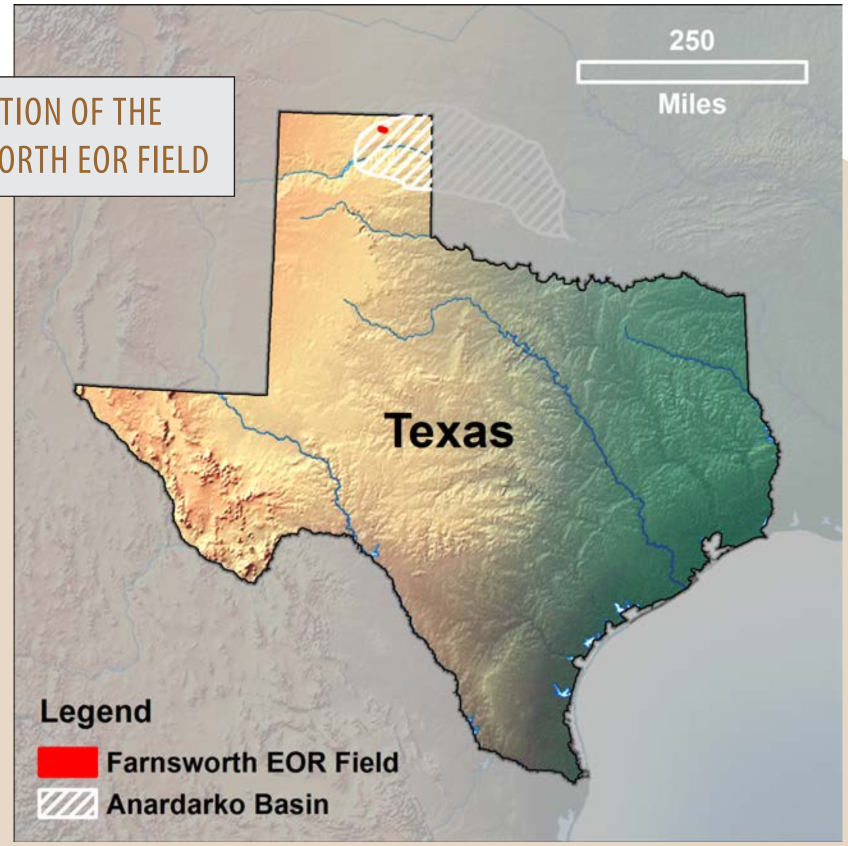


SWP Large-Scale Field Project Field Test

SWP has teamed up with Chaparral Energy of Oklahoma City to conduct a new CCUS project with 100 percent anthropogenic CO_2. The new pilot study of large-scale CO_2 injection will utilize Chaparral's Farnsworth Unit in the Texas panhandle. Highlights of the project, which will begin in Summer 2012, include—

- Anthropogenic CO_2 from a fertilizer plant (Agrium in Borger, Texas) and ethanol plant (Arkalon Energy in Liberal, Kansas)
- CO_2 injection into the Morrow Sandstone, an oil-producing formation in the Anadarko Basin, to enhance oil recovery and store CO_2
- Injection of more than 1 million metric tons of CO_2 over the project's 5-year span

LOCATION OF THE FARNSWORTH EOR FIELD

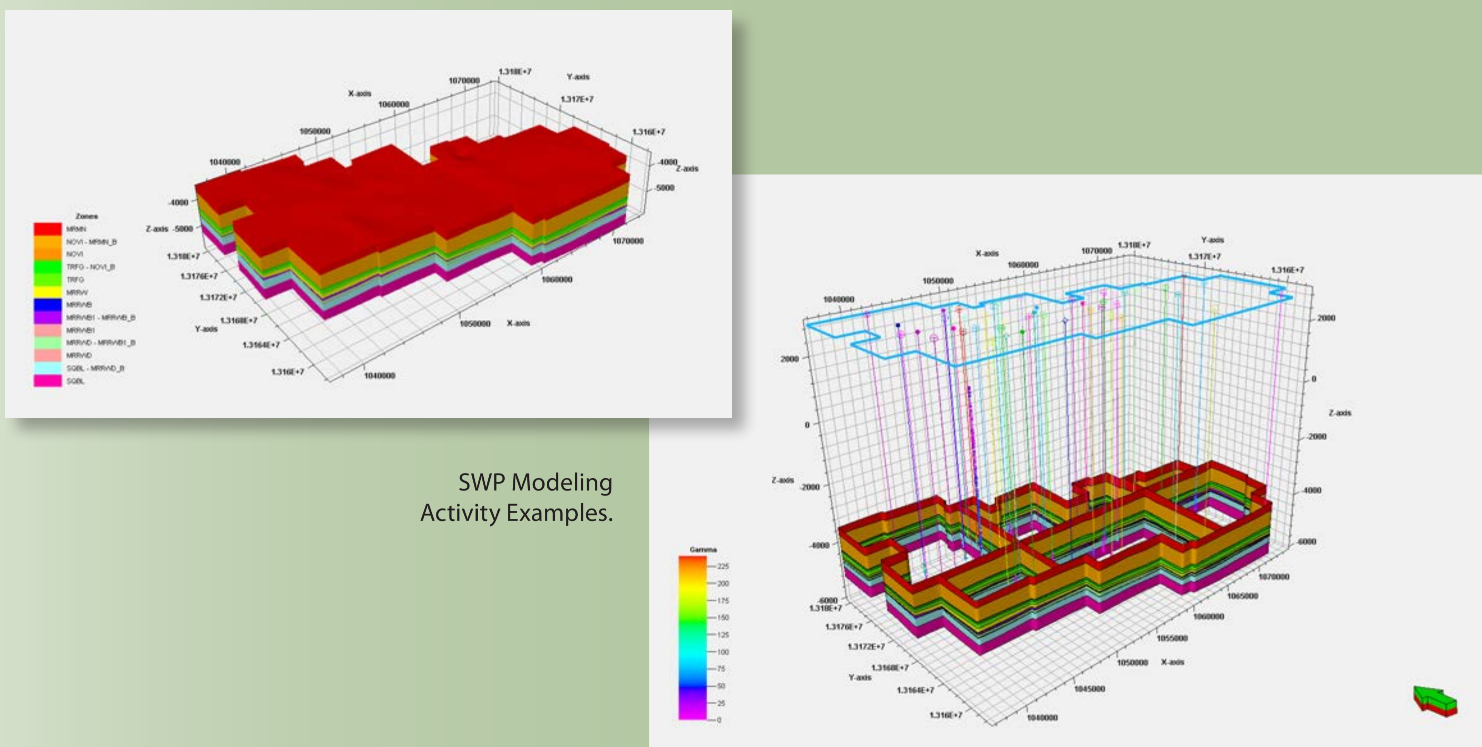


Comprehensive Geologic Characterization

- 3-D Seismic and vertical seismic profiles
- Two new wells drilled, each with core recovery and petrophysical logging
- Core analyses for fundamental hydraulic and geomechanical properties
- Construction of a detailed 3-D geologic model

Comprehensive Monitoring Activities

- Passive seismic
- Repeat vertical seismic profiles and crosswell tomography
- Groundwater sampling
- Soil CO_2 and methane flux
- CO_2 and water tracers
- Surface deformation (GPS and InSAR)
- Gravity and electrical self-potential

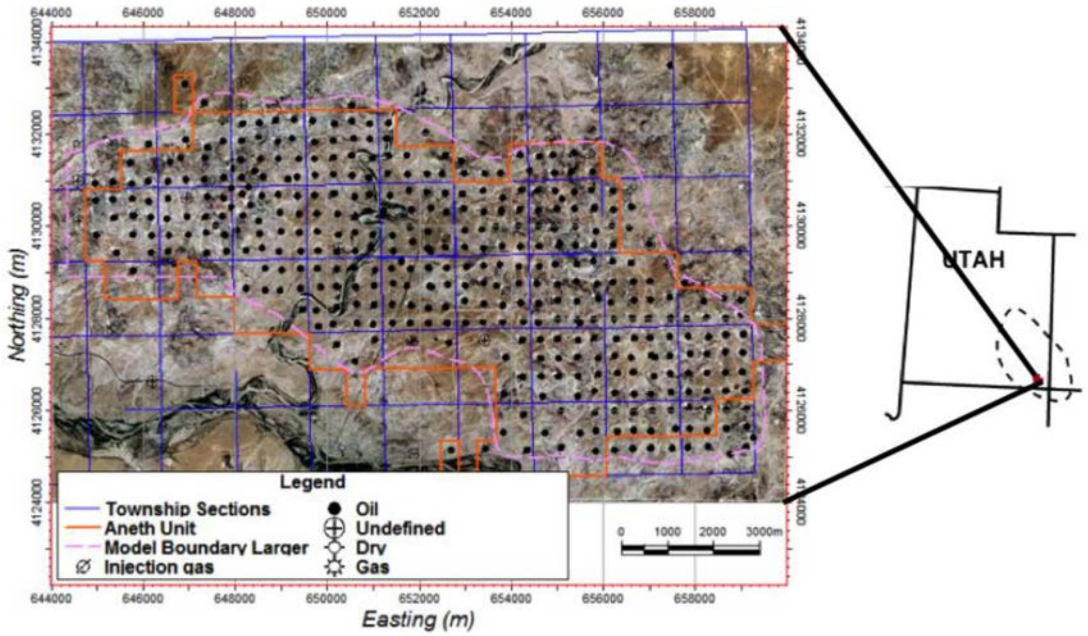


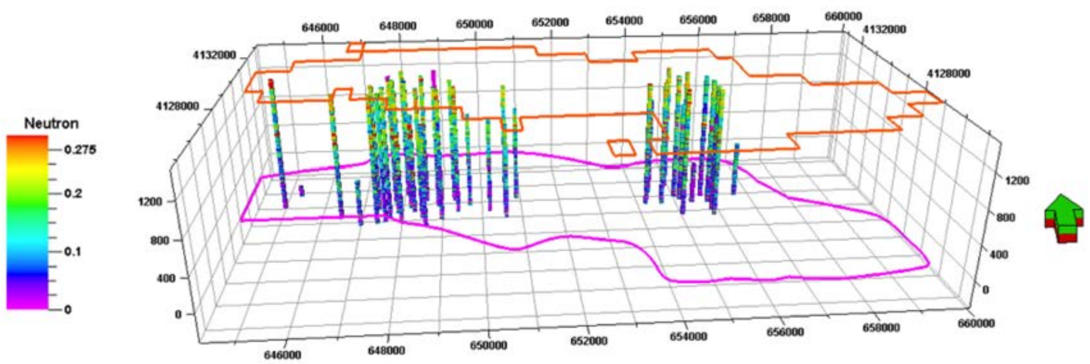
SWP Modeling Activity Examples.

SWP Model Development

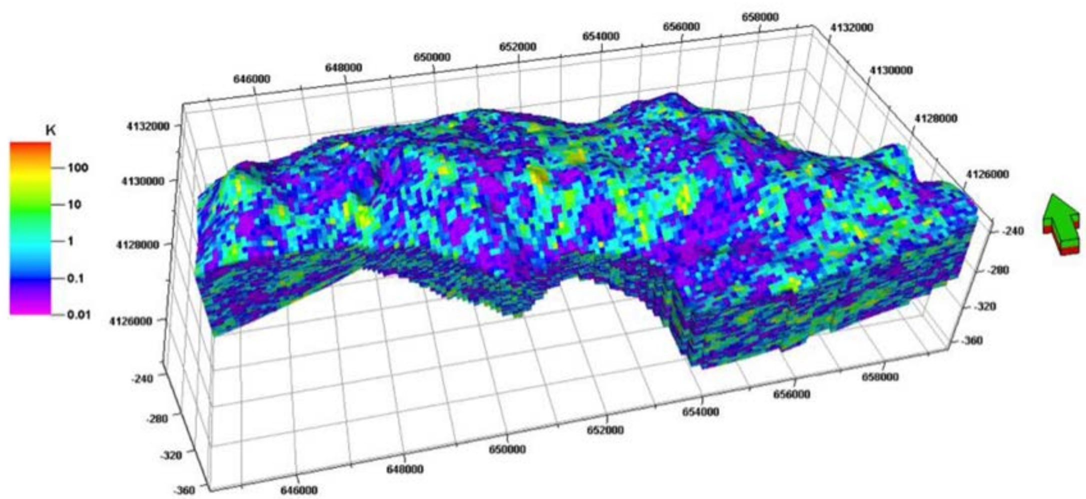
The Aneth field is Utah's most productive oil field, yielding approximately 149 million barrels of oil since its discovery in 1956. From 2007 to 2009, SWP designed and deployed a medium-scale field pilot test of geologic CO_2 storage in the Aneth field. The Aneth test is one of three geologic pilot tests conducted under the auspices of the SWP.

SWP researchers developed a geologic model of the Aneth Field and conducted numerical simulations to demonstrate efficacy of CO_2 storage technologies within producing oil reservoirs. Available stratigraphic, petrophysical, and geophysical information from the Aneth site were collected and compiled, and acquired well logs were digitized and integrated into the model development. The petrophysical data were reviewed to estimate essential properties, such as porosity and permeability. Based on the compiled geologic data, a site-specific static geologic model was constructed. The petrophysical properties (porosity and permeability) were populated into the static model using porosity logs and correlations derived from the petrophysical properties of well logs. The constructed static model served as a base for subsequent numerical simulations that assessed CO_2 migration and behavior.

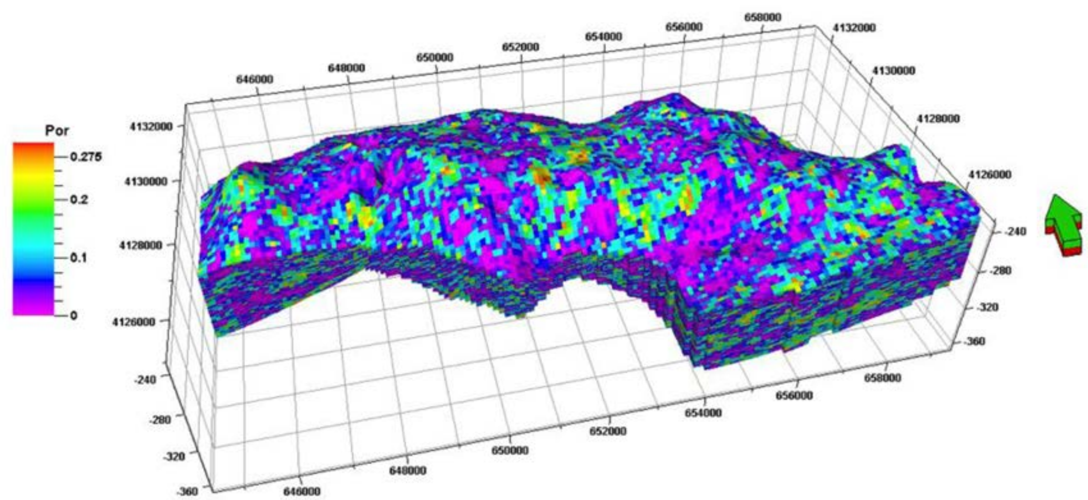




Geologic model of the Aneth field showing log data.



Geologic model of the Aneth field showing porosity.

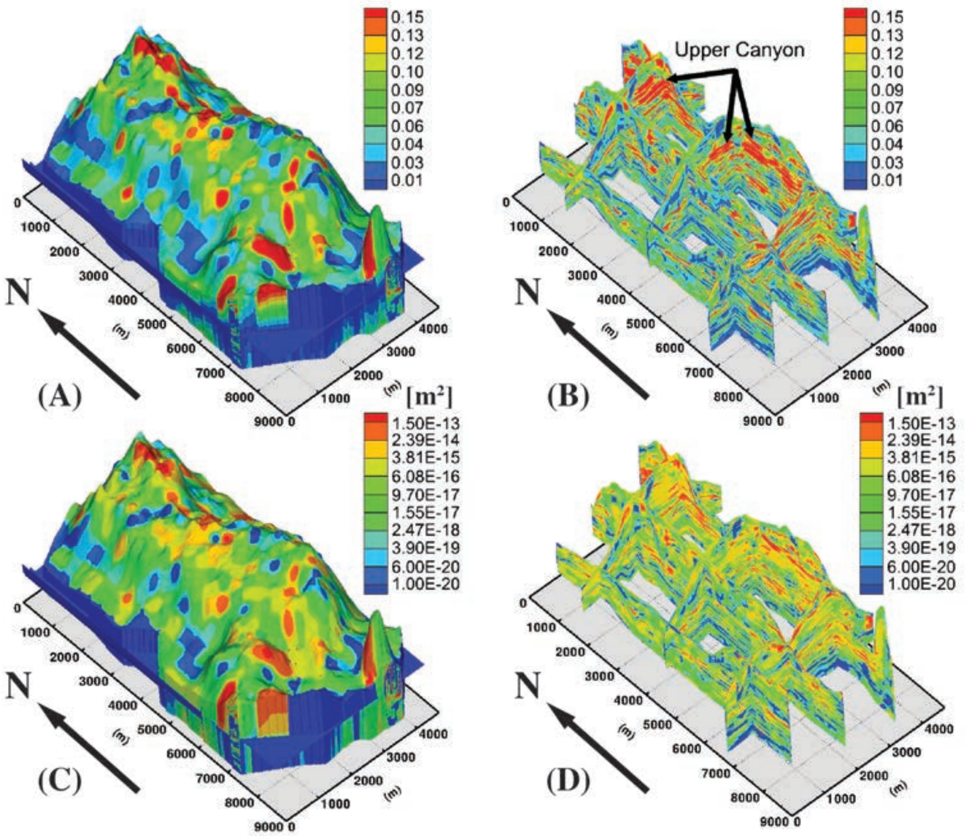


Geologic model of the Aneth field showing permeability.

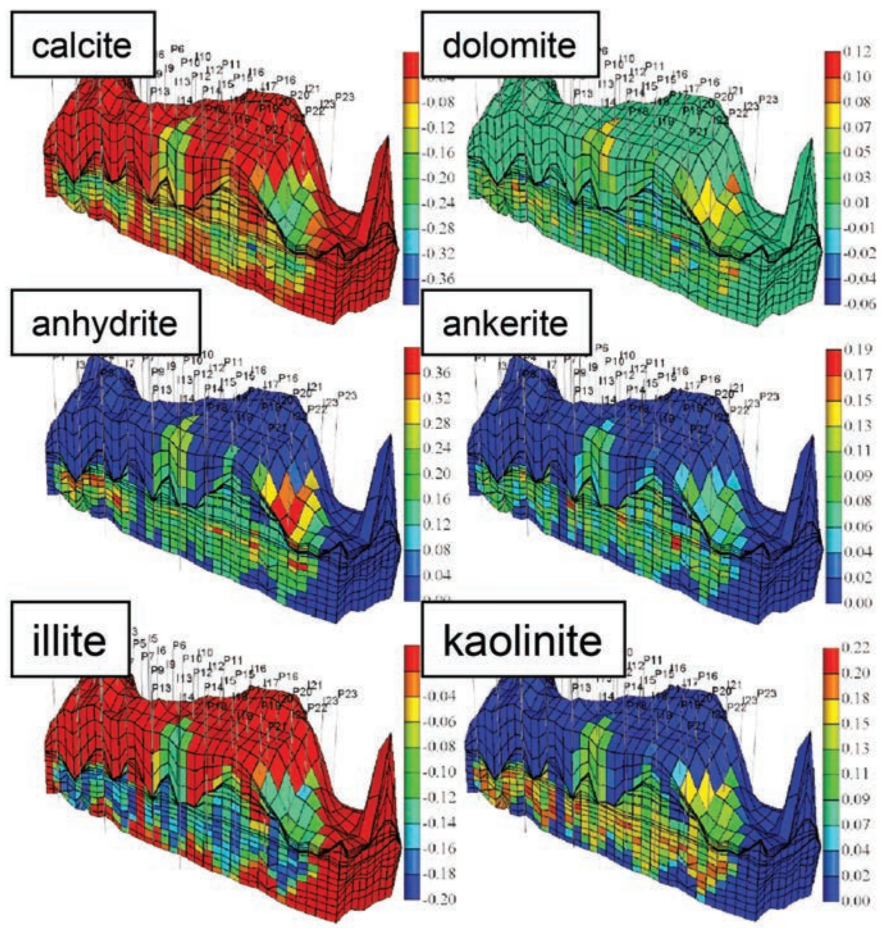
SWP Small-Scale Field Project Results: Evaluation of Trapping Mechanisms in Sacroc, Texas

The SACROC Unit, near Snyder, Texas (Permian Basin), is one of SWP's small-scale test sites. SWP focused on the northern platform area of the SACROC Unit where approximately 7 million metric tons (7.72 million tons) of CO_2 have been injected since 1972 as part of the field's EOR process. In the SACROC northern platform model, researchers defined porosity distributions based on extensive analyses of both 3-D seismic surveys and calibrated well logging data from 368 locations. Permeability distributions were estimated from porosity fields. The resulting 3-D model representing the SACROC Unit consists of more than 9.4 million elements that characterize detailed heterogeneous reservoir geology.

Using the 3-D model with detailed fluid injection and production history data, as well as a vast amount of field data, two separate models were developed to evaluate competing CO_2 trapping mechanisms: dissolution of CO_2 in oil (oil-solubility trapping), and mobile CO_2. In the 30-year injection period from 1972 to 2002, these were the two most commonly used trapping mechanisms during the entire simulation period. While dense-phase CO_2 is mobile near the injection wells due to the high CO_2 saturation, it behaves similar to residually trapped CO_2 because of the small density contrast between oil and CO_2.



Modeled porosity and permeability of the SACROC Unit, northern platform.

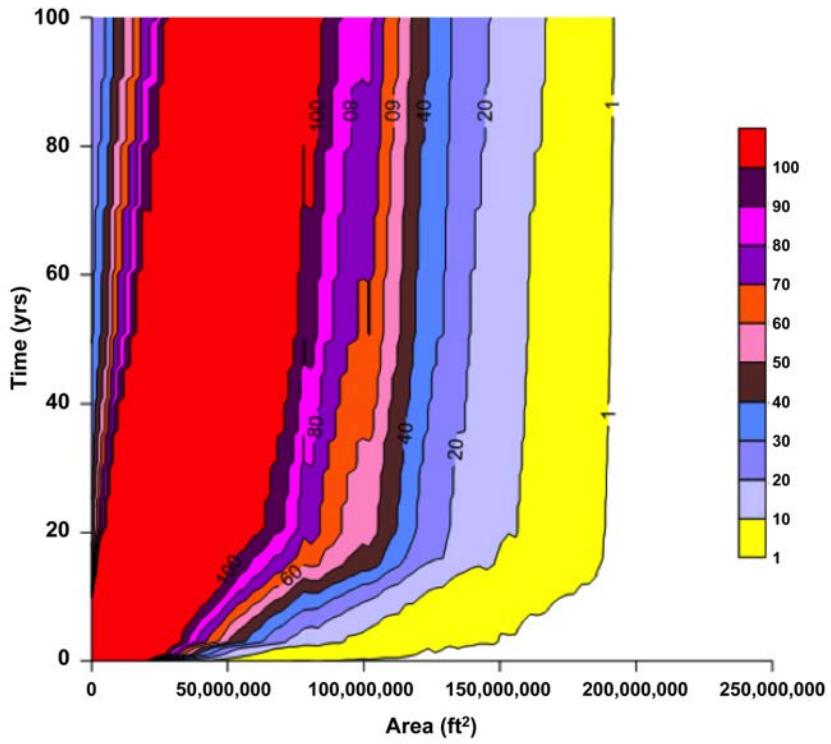


Simulated mineral trapping within the SACROC Unit, northern platform.

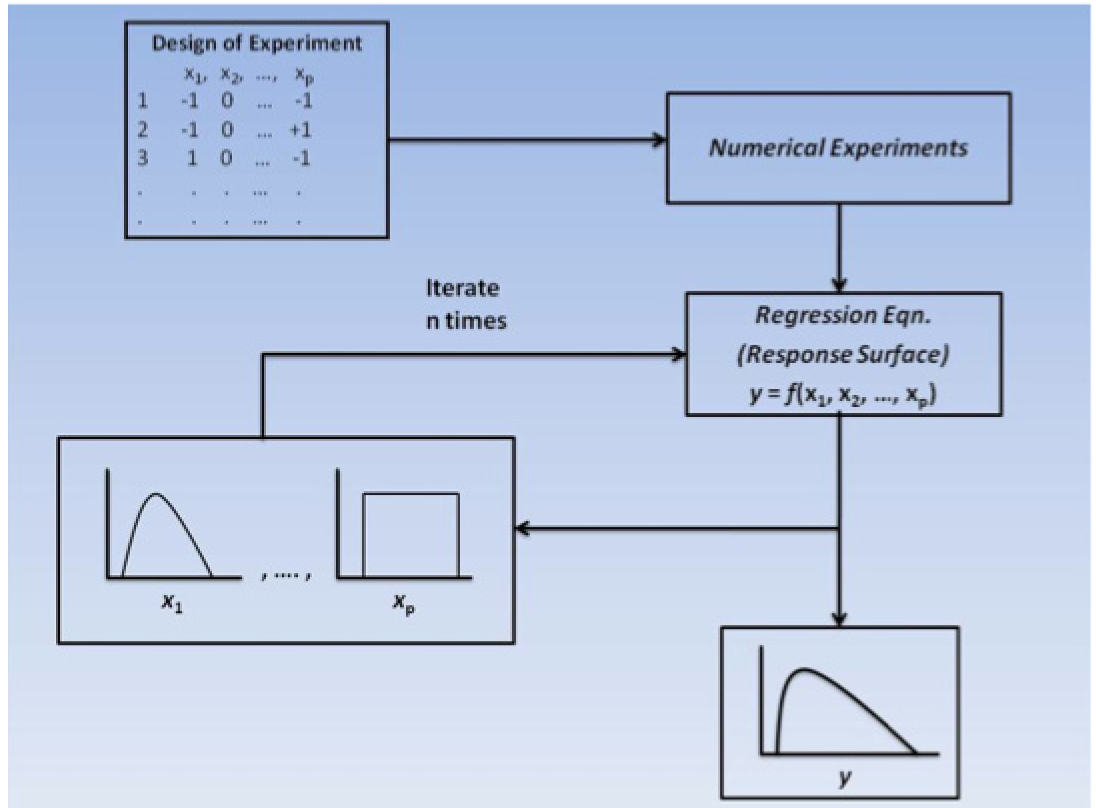
SWP Risk Analysis: Probablistic Area of Review Prediction of CO_2 Storage

As part of the process to fully characterize a site for CO_2 storage potential, SWP performs a risk assessment to evaluate the extent of migration for a CO_2 plume theoretically injected at a rate of 1 million tons per year for 2 years. Two methods are used: (1) the response surface method and (2) the Monte Carlo simulation approach.

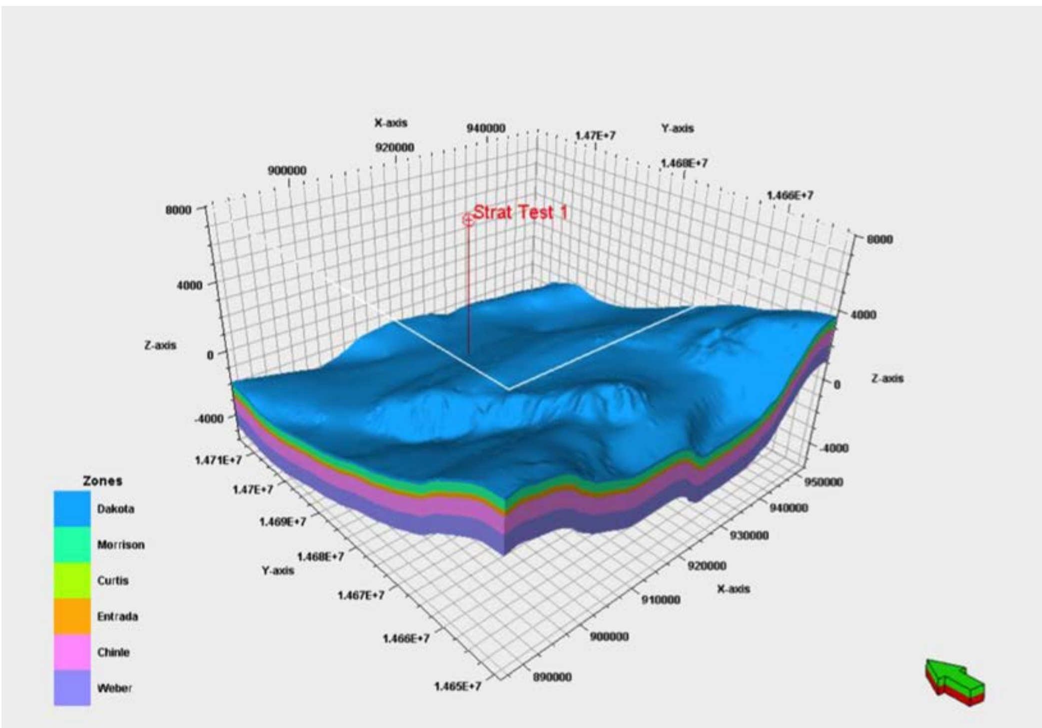
The outcome of the simulations for many models suggests that a simulated plume will continue to spread some 100 years after injection ceases. However, more accurate petrophysical data from core samples recovered from project areas will help refine the area of review.



Contour map of the frequencies in CO_2 plume extent for a target reservoir.



The simulation involves the utilization of response surface method associated with the Box-Behnken design and corresponding numerical modeling experiments.



Model of Aneth field.

SWP CCUS Training Center

The goal of SWP's CCUS Training and Research in Energy Decision Making is to generate interest in and understanding of CCUS technologies. The Training and Research in Energy Decision Making Program involves both the public and private sectors and focuses on the scientific and social implications of CCUS technologies within the southwest United States, with links to national and international contexts. This includes the use of technologies for the mitigation of global climate change while addressing current and future energy needs. The objectives are to develop and make accessible—

- Academic programs and curricula
- Specialized classes
- Continuing education
- Professional development opportunities
- Public awareness materials and activities

The Adventures of Carbon Bond 2.0©.

TREND field trip in the desert.

TREND
TRAINING AND RESEARCH IN ENERGY DECISION MAKING

Training Completed as of March 31, 2012:

Total Formal Education Contact
2,853 total contact hours

CEU/PDU Contact
678 contact hours

University Coursework Contact
1,545 contact hours

High School Contact
630 contact hours

West Coast Regional Carbon Sequestration Partnership

The West Coast Regional Carbon Sequestration Partnership (WESTCARB) region—Alaska, Arizona, California, Hawaii, Nevada, Oregon, Washington, and the Canadian province of British Columbia—is characterized by a wealth of natural resources, varied ecosystems, complex geology, and a culturally diverse population that has both a strong entrepreneurial spirit and sense of environmental responsibility. The region has one of North America's broadest mixes of CO_2 sources, as well as numerous opportunities to curb CO_2 emissions through carbon utilization and storage.

WESTCARB, led by the California Energy Commission in partnership with Lawrence Berkeley and Lawrence Livermore National Laboratories, includes more than 100 members from public agencies, private companies, universities, and nonprofit organizations. WESTCARB's goals are to characterize regional opportunities for geologic carbon storage; validate promising storage options through field tests; and facilitate CO_2 utilization and geologic storage at commercial scale.

WESTCARB's geologic characterization studies show that the saline formations in the region's broadly distributed sedimentary basins have the potential to store hundreds of years' worth of CO_2 emissions from stationary sources. The region also offers opportunities for coupling geologic carbon storage with enhanced hydrocarbon and geothermal energy production.

WESTCARB's commitment to public outreach and education fosters dialog among the region's CCUS stakeholders. Policymakers in the region have been active in addressing climate change through laws, regulations, and initiatives to reduce greenhouse gas emissions, and they have relied on WESTCARB to provide accurate information on CCUS. Stakeholders see CCUS as an essential tool for curbing atmospheric CO_2 buildup from fossil fuel use while sustaining healthy economies.

Contact

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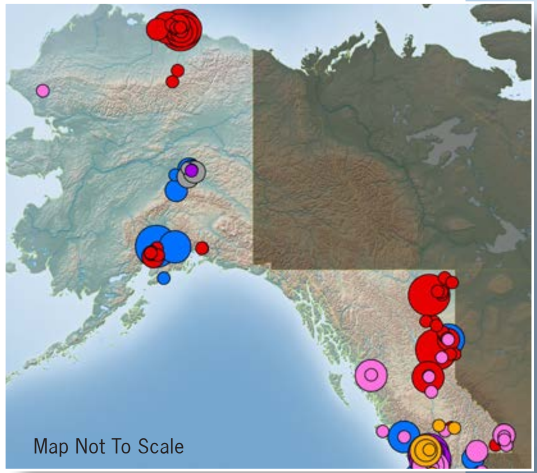
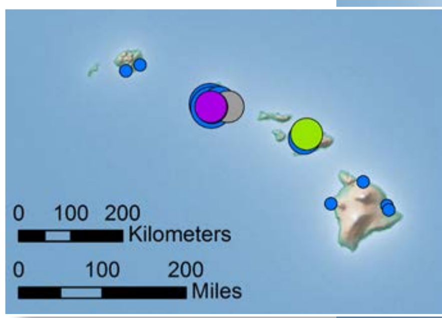
WESTCARB CO_2 Sources

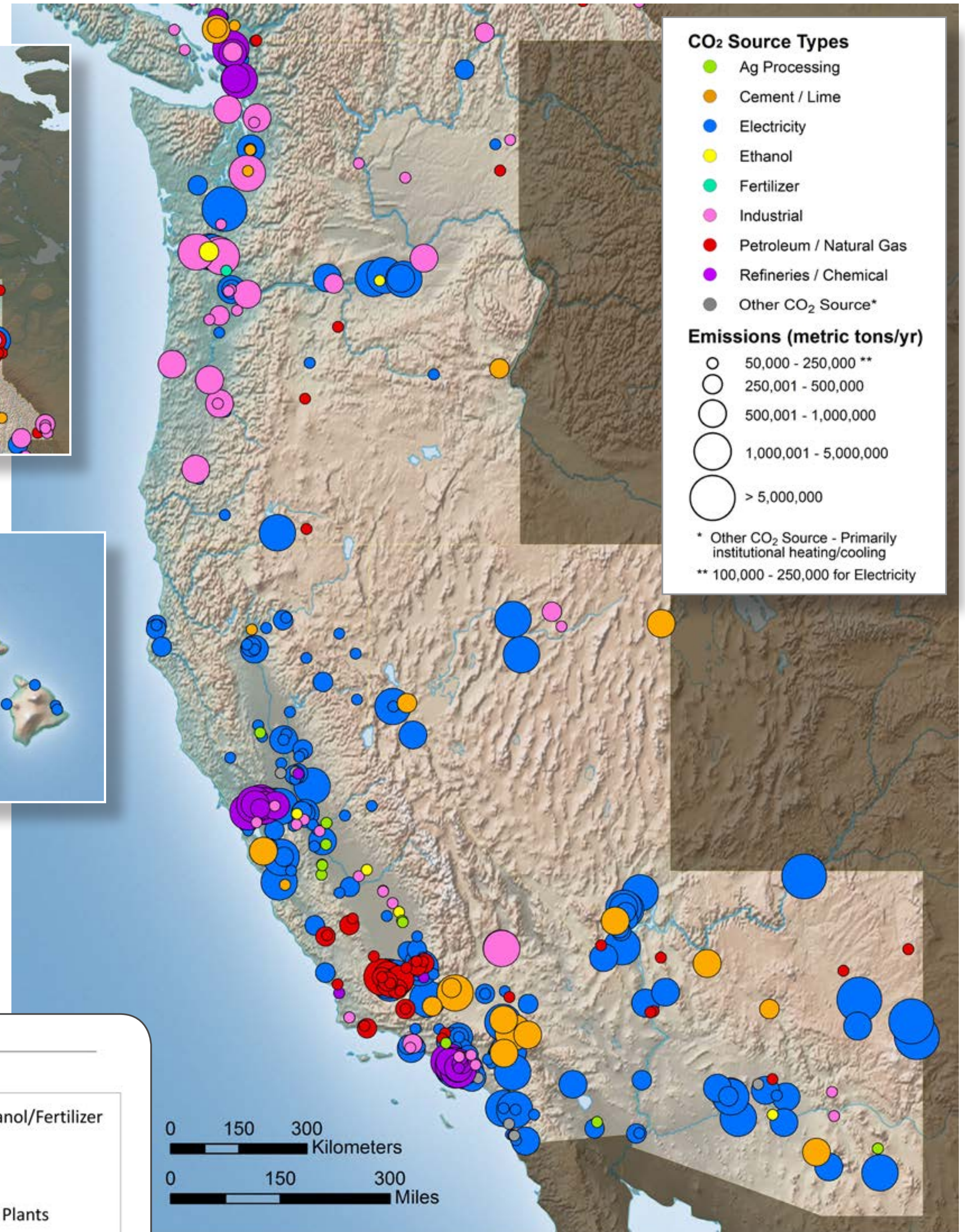
Electric power plants are the largest stationary CO_2 source type in the WESTCARB region, although the fuel mix used for power generation varies among WESTCARB states. Arizona is home to the region's largest coal-fired plants, whereas natural gas combined cycle plants are predominant in California and are common in several other states. Hawaii mostly uses oil-fired generation. Alaska is unique within the WESTCARB region in that oil and natural gas processing facilities are the greatest contributors to CO_2 emissions. Oil refining and chemical plants are also major emission sources in California.

Throughout the region, other industrial CO_2 sources include cement and lime plants, aluminum smelters, pulp and paper mills, steel mills, ethanol fermenters, and fertilizer plants. Mobile source emissions constitute a large percentage of total emissions in several WESTCARB states. This underscores the importance of developing geologic storage options for traditional and alternative transportation fuel plants to offset these emissions. In addition, the number of alternative fuel or biofuel plants has the potential to rapidly grow as the industry expands into low-carbon fuels. Adding CCUS to biofuel plants offers the opportunity for net negative CO_2 emissions.

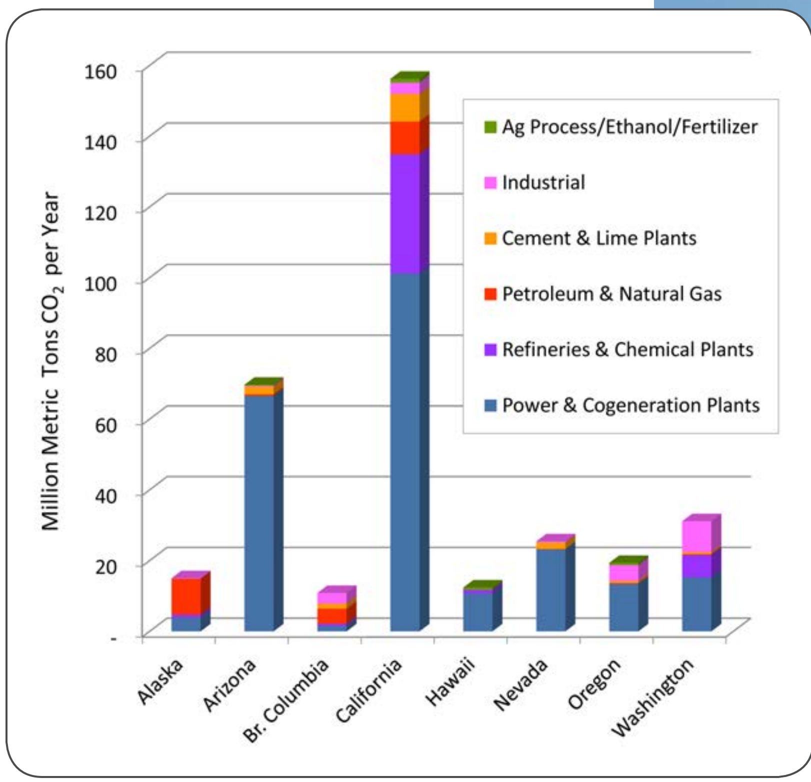
Overall, the WESTCARB CO_2 sources database includes information on more than 500 of the largest emitting stationary sources in the WESTCARB region. Geographic information system tools for analyzing WESTCARB stationary sources and assessing their proximity to potential regional CO_2 storage locations are available through the WESTCARB Carbon Atlas and through NATCARB (http://www.netl.doe.gov/technologies/carbon_seq/natcarb/index.html).



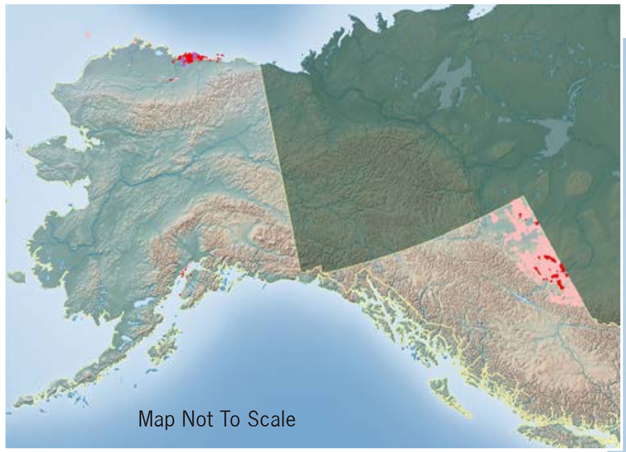


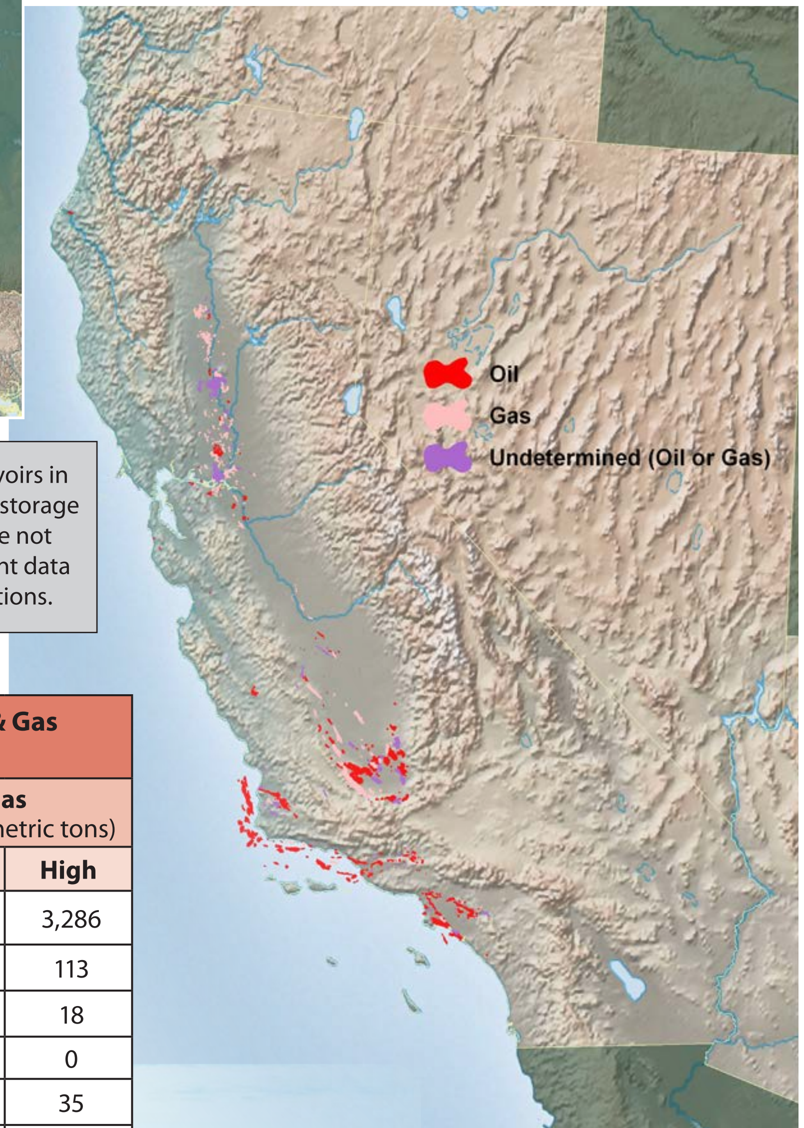


Estimated CO_2 Emissions by State/Province in the WESTCARB Region	
State/Province	**Million Metric Tons CO_2/yr**
Alaska	15
Arizona	70
British Columbia	11
California	156
Hawaii	12
Nevada	25
Oregon	19
Washington	31
Total	**340**



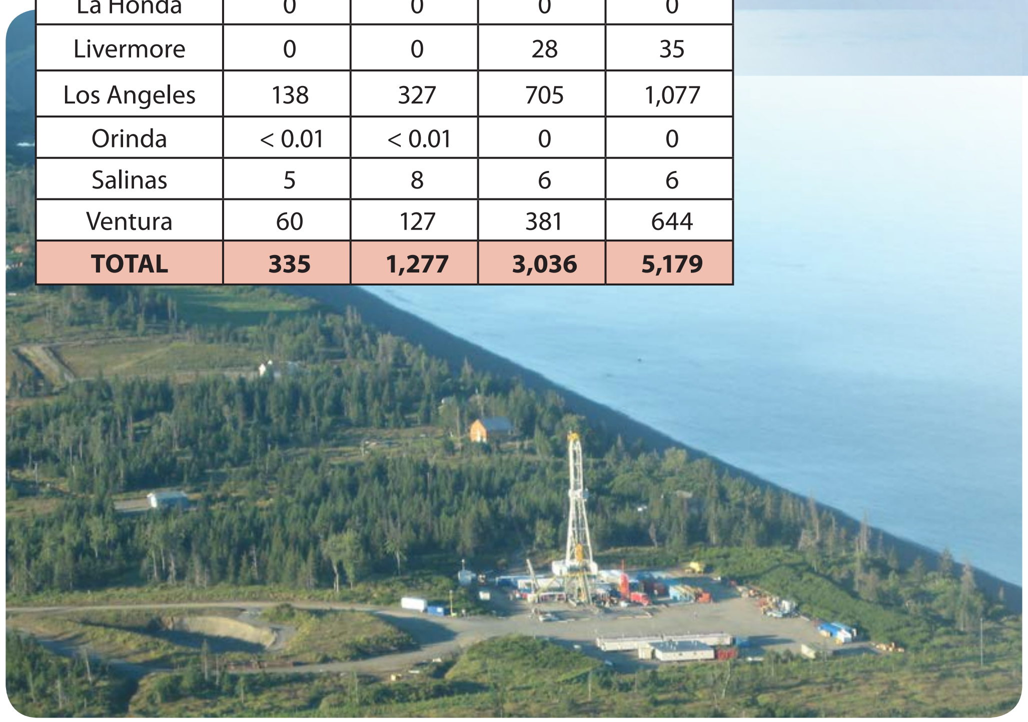
WESTCARB Oil and Gas Reservoirs





Screened oil and gas reservoirs in the WESTCARB region have storage potential, but volumes are not estimated due to insufficient data or pending future evaluations.

Estimated CO_2 Storage Resource in Oil & Gas Reservoirs in California Basins				
Basin	Oil (million metric tons)		Gas (million metric tons)	
	Low	High	Low	High
Central Valley	124	771	1,843	3,286
Cuyama	8	43	55	113
Eel River	< 0.01	< 0.01	18	18
La Honda	0	0	0	0
Livermore	0	0	28	35
Los Angeles	138	327	705	1,077
Orinda	< 0.01	< 0.01	0	0
Salinas	5	8	6	6
Ventura	60	127	381	644
TOTAL	**335**	**1,277**	**3,036**	**5,179**



Cook Inlet, Southern Kenai Peninsula, Alaska. (Photo courtesy of Pioneer Natural Resources)

In the WESTCARB region, major oil and gas fields represent both storage targets and opportunities for EOR and enhanced natural gas recovery.

In California, most onshore oil reservoirs are found in the southern San Joaquin Basin, Los Angeles Basin, and Ventura Basin. Based on estimates of ultimately recoverable oil reserves, WESTCARB investigators have identified approximately 0.3 billion–1.3 billion metric tons (0.4 billion–1.4 billion tons) of CO_2 storage resource potential.

WESTCARB estimates the CO_2 storage resource potential in California natural gas reservoirs at 3.0 billion–5.2 billion metric tons (3.3 billion–5.7 billion tons). Regionally, California's Central Valley has the largest CO_2 storage resource potential, in the range of 2.0 billion–4.1 billion metric tons (2.2 billion–4.5 billion tons). The southern portion of the basin is home to some of California's largest natural gas fields. Now largely depleted, these fields may represent opportunities for CO_2 storage following cessation of commercial natural gas production or in conjunction with the use of CO_2 for enhanced natural gas recovery, a technology currently in the research and development stage.

Offshore California, oil and gas accumulations have been found in the Santa Maria, Ventura, and Los Angeles Basins. Excluding areas with fractured shales, which are not prime candidates for CO_2 storage, estimated CO_2 storage resource for the known developed and undeveloped offshore oil and gas fields within conventional sandstone reservoirs of the Los Angeles and Ventura Basins is 240 million metric tons (265 million tons).

In Alaska, the hydrocarbon reservoirs of the North Slope and Cook Inlet are of interest to researchers because of their proximity to large stationary CO_2 sources and the potential for CO_2-EOR.

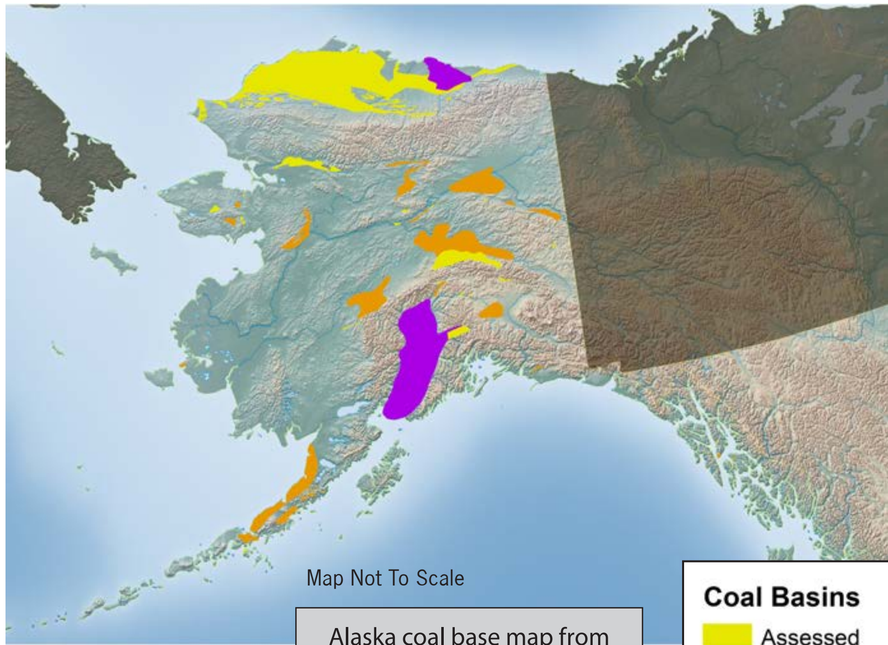
In conjunction with geologic storage, additional production may be achieved in some oil fields through CO_2-EOR, even when secondary recovery methods have already been applied.

WESTCARB
Unmineable Coal

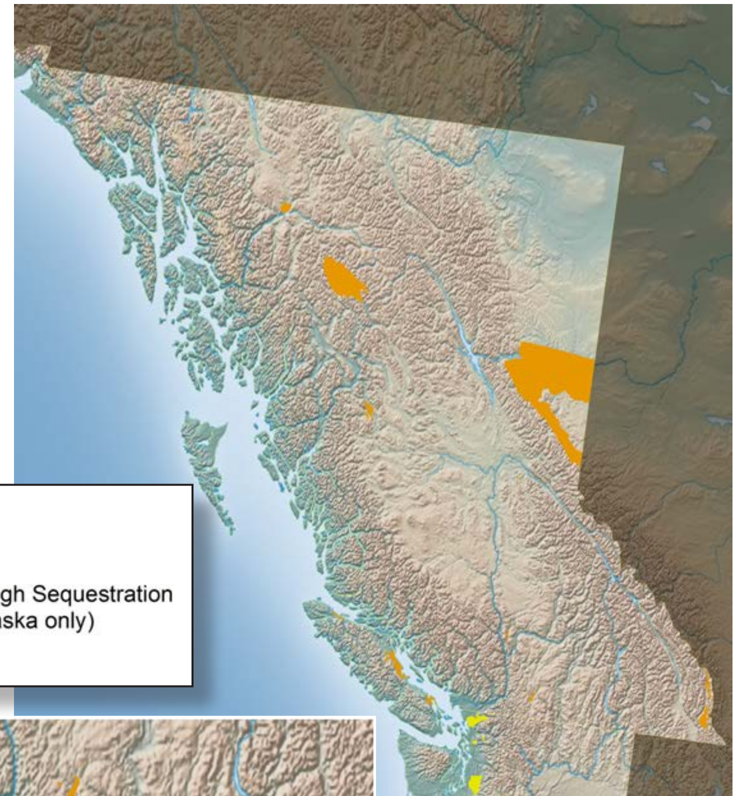
Opportunities for geologic CO_2 storage in unmineable coal seams within the WESTCARB region are predominantly found in the Pacific Northwest and Alaska. In the Pacific Northwest, three deep coalbed deposits are promising storage locations: the Bellingham Basin in northwestern Washington; the coals of the Puget Sound region, south and east of the Seattle-Tacoma metropolitan area; and small, deep coal deposits in southwestern Oregon.

Coal seams in the Puget Sound region have been previously tested for coalbed methane production. Initial studies show that the subsurface extent of the coal basins represents an area greater than 2,500 square kilometers (950 square miles). Analysis indicates a prospective coal seam thickness of 30 meters (100 feet), a CO_2 sorption capacity of 20–24 cubic meters (700–850 cubic feet) CO_2 per ton of coal, and a permeability of approximately 5 millidarcies. The estimated CO_2 storage resource potential in this area is 1.3 billion metric tons (1.5 billion tons), and the estimated recoverable coalbed methane is 57–570 billion cubic meters(2–20 trillion cubic feet).

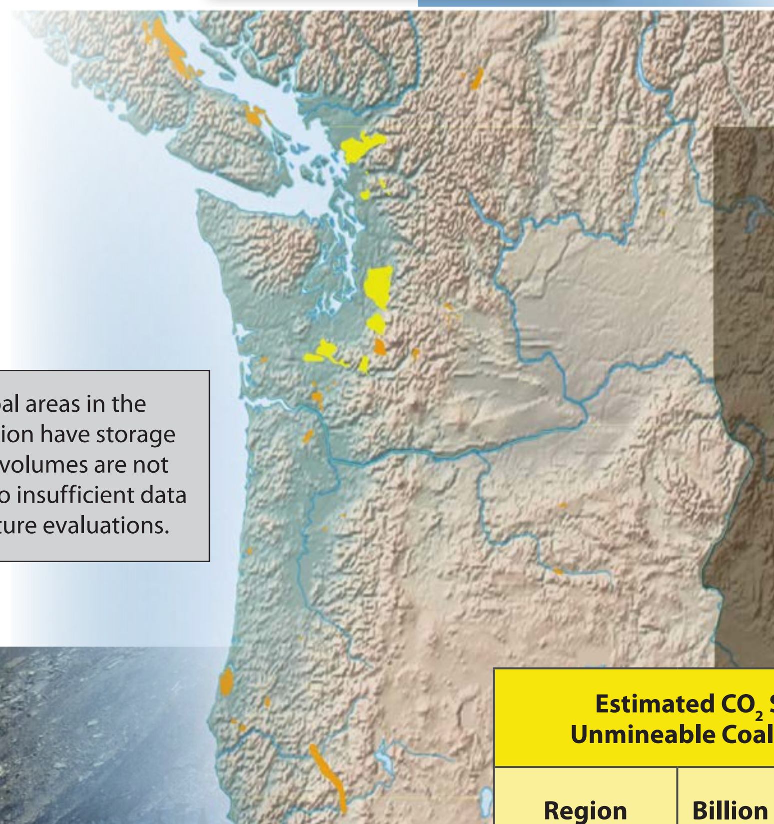
Although coal mining in Alaska has been limited, the state contains major coal deposits that range from shallow to more than 2,000 meters (6,500 feet) deep. Alaska's coalbed methane resources are estimated to be approximately 22 trillion cubic meters(780 trillion cubic feet), which is comparable to the coalbed methane resources in all of the lower 48 states. However, only a portion of the state's coal resource is considered favorable for CO_2 storage due to coal quality, permeability, seam geometry, surface access, faulting, permafrost, depositional environment, and other site-specific conditions. The coal seam CO_2 storage opportunities of the highest potential lie in unmineable coalbeds in the North Slope and Cook Inlet regions, which are accessible and have coals of suitable thickness, depth, and permeability. Preliminary estimates reveal a geologic CO_2 storage resource of approximately 24 billion metric tons (26 billion tons) in these Alaskan coal seams.



Alaska coal base map from Alaska Division of Geological and Geophysical Surveys Special Report 37, 1986.



Coal Basins
- Assessed
- Assessed, High Sequestration Potential (Alaska only)
- Screened



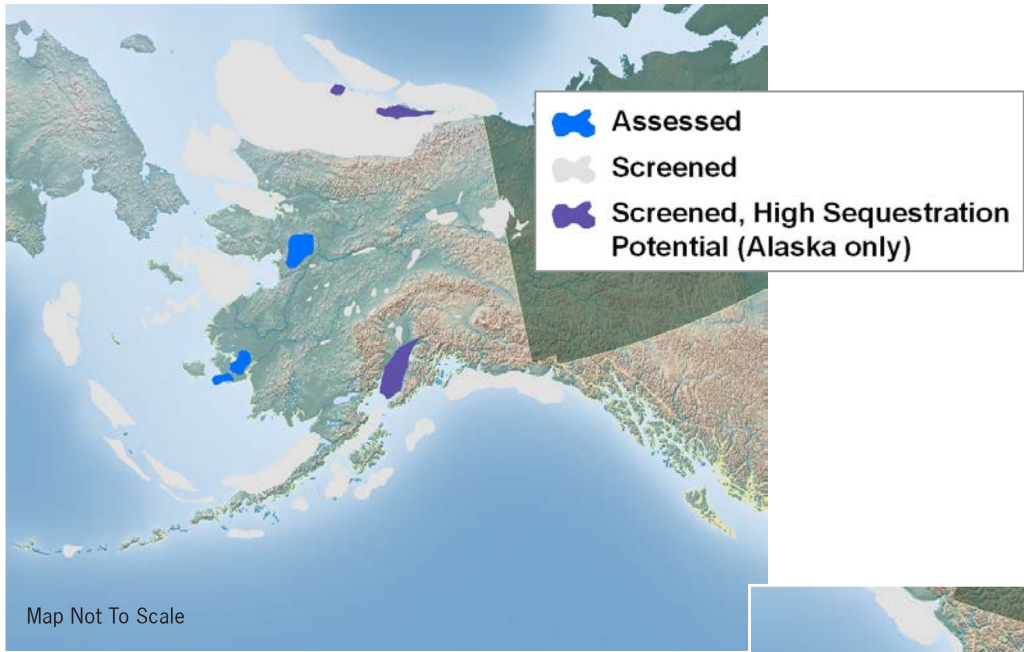
Screened coal areas in the WESTCARB region have storage potential, but volumes are not estimated due to insufficient data or pending future evaluations.

TransAlta's 1400 MW coal-fired power plant in Centralia, Washington.

Studying a coalbed on the Kukpowruk River, North Slope Alaska. (Photo courtesy of Gary D. Stricker USGS)

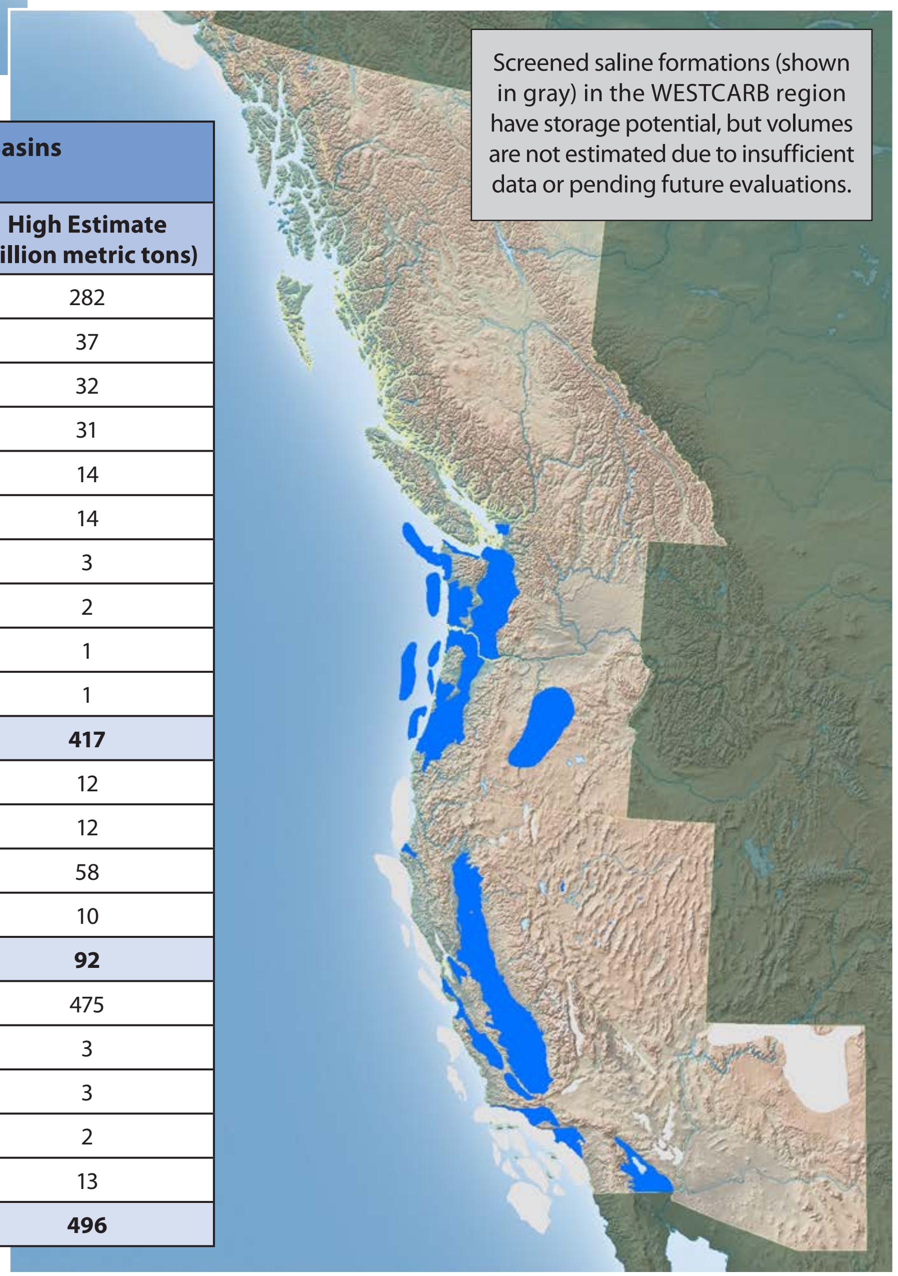
Estimated CO_2 Storage Resource in Unmineable Coal in WESTCARB Region		
Region	**Billion Metric Tons**	**Billion Tons**
Puget Sound	1.3	1.5
Alaska	24	26

WESTCARB Saline Formations



Deep sedimentary basins are broadly distributed throughout the WESTCARB region. Many contain saline formations suitable for CO_2 storage based on depth, sealing formations, and brine waters that preclude use as potable water resources. In California, Cenozoic sedimentary basins offer some of the best opportunities for geologic storage. These basins exhibit wide areal distribution; thick sedimentary sections containing multiple widespread marine sandstones; and thick, laterally persistent marine shale seals. In some basins, petrophysical data from oil and gas development are available to support assessments.

California may also have potential for CO_2 storage in offshore basins, although the lack of available data has limited assessment to areas of oil and gas exploration. GeoMechanics Technologies is currently conducting a study of the Pliocene and Miocene formations of the Wilmington Graben, directly offshore from the Los Angeles and Long Beach harbor areas. Onshore, WESTCARB ranks the San Joaquin, Sacramento, Ventura, Los Angeles, and Eel River Basins as the most promising in California. Researchers estimate the aggregate CO_2 storage resource of the largest onshore basins in the range of 30 billion to 420 billion metric tons (30 billion to 460 billion tons) of CO_2 (more information available in the ARRA Site Characterization section).



Estimated CO_2 Storage Resource – Sedimentary Basins in California, Oregon, and Washington			
	Basin	Low Estimate (billion metric tons)	High Estimate (billion metric tons)
California	Central Valley	21	282
	Salton Trough	3	37
	Ventura Basin	2	32
	Los Angeles Basin	2	31
	Cuyama Basin	1	14
	Salinas Basin	1	14
	La Honda Basin	< 1	3
	Eel River Basin	< 1	2
	Orinda Basin	< 1	1
	Livermore Basin	< 1	1
	TOTAL	**30**	**417**
Oregon	Astoria-Nehalem Basin	1	12
	Ochoco Basin	1	12
	Tyee-Umpqua Basin	4	58
	Willamette Trough	1	10
	TOTAL	**7**	**92**
Washington	Puget Trough	35	475
	Tofino-Fuca Basin	< 1	3
	West Olympic Basin	< 1	3
	Whatcom Basin	< 1	2
	Willapa Hills Basin	1	13
	TOTAL	**36**	**496**

In Oregon and Washington, western coastal basins containing sandstone and shale sequences up to 10,000 meters (33,000 feet) thick have sites that appear suitable for CO_2 storage. The total CO_2 storage resource for these sedimentary basins is in the range of 40 billion to 590 billion metric tons (50 billion to 650 billion tons). The basin with the largest CO_2 storage potential is Washington's Puget Trough.

In Arizona, formations underlying the Colorado Plateau region, where most of the state's large coal-fired power plants are located, offer potential storage targets and seals that are laterally extensive and up to hundreds of feet thick. Elsewhere in Arizona, Paleozoic formations and Tertiary basins may also represent storage opportunities. These are currently the focus of a WESTCARB study.

In Alaska, difficulties with site access and harsh working environments place limits on characterization and utilization of the CO_2 storage resource. Researchers are focusing on the Cook Inlet Basin and North Slope, where proximity to industrial CO_2 sources and extensive infrastructure, as well as ample characterization data from oil and gas exploration, make CO_2 storage more feasible.

For CO_2 storage in Nevada, Granite Springs Valley in Pershing County, Antelope and Reese River Valleys in Lander County, and Ione Valley in Nye County appear sufficiently large areally and are filled with sediments and volcanic rocks. Site characterization studies are being initiated to determine if CO_2 storage resource exists beneath these valleys.

Characterizing Areas with High CCUS Potential in Arizona

Within the WESTCARB region, the highest concentration of coal-fired power plants is found in Arizona, particularly on the Colorado Plateau in the northeastern quadrant of the state. These plants account for more than 40 million metric tons (44 million tons) of CO_2 per year. The Colorado Plateau is a stable geologic province with thick sedimentary rock formations; however, detailed information on the Plateau's deep formations is limited because there are few deep wells.

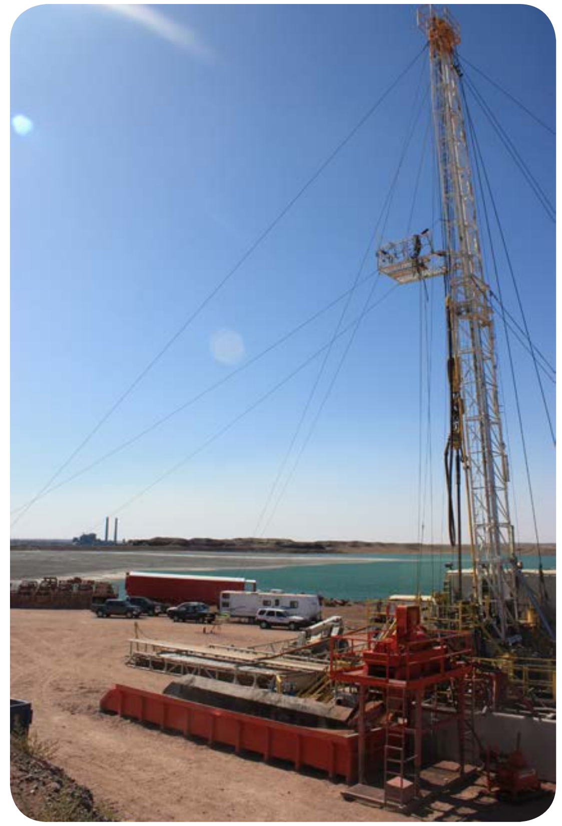
To expand the knowledge base on Colorado Plateau formations suitable for CO_2 storage, WESTCARB drilled a characterization well on Arizona Public Service Company land near the Cholla Power Plant, at the southern edge of the plateau. Co-sponsored by a consortium of Arizona utilities and an energy company, the well penetrated the entire sedimentary sequence to a depth of 1,170 meters (3,850 feet). Mudlogging, wireline logging, core sample analysis, and formation permeability tests confirmed the presence of suitable sealing formations and the high salinity of formation brines, but the target formations for CO_2 storage proved to be compacted carbonates rather than the permeable sandstones that had been expected.

Despite a localized finding of insufficient permeability, the overall prospect for large CO_2 storage resources in the Colorado Plateau remains excellent because of the thickness of deep-lying sandstone formations and the presence of good seals.

Arizona also has coal and natural gas-fired power plants and cement plants that are located in the Basin and Range geologic province. The Arizona Geological Survey is currently assembling data for 88 Cenozoic sedimentary basins in this area, with a focus on formation water salinities and formation volumes below 800 meters (2,600 feet) deep, which is where natural hydrostatic pressure keeps CO_2 in the dense-phase state efficient for storage. Initial findings indicate that 10 relatively large basins represent approximately 70 percent of the deep-basin volume in the Basin and Range province. The largest is the Safford-San Simeon Basin, east of Phoenix and Tucson, with a volume of 2,296 cubic kilometers (550 cubic miles) below 800 meters. This basin alone may have the potential to store 100 or more years' worth of CO_2 emissions from nearby power plants.

Arizona geologic provinces and coal-fired power plants in the northeastern quadrant.

Arizona's distinctive red sandstone formations are apparent in the strata of many canyons and outcrops.



WESTCARB geologic characterization well near the APS Cholla Power Plant.

WESTCARB utility funders and contractors tour the drill site at Cholla

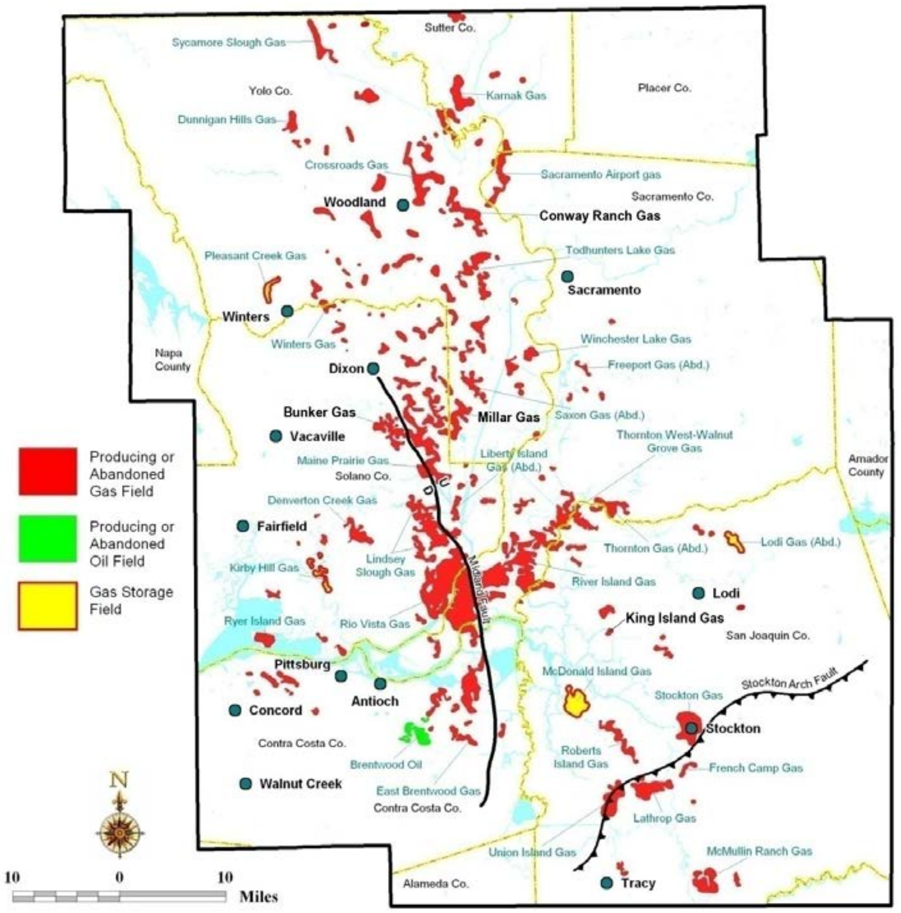
Discussion following a community meeting in Holbrook, Arizona.

Characterizing Areas with High CCUS Potential in California

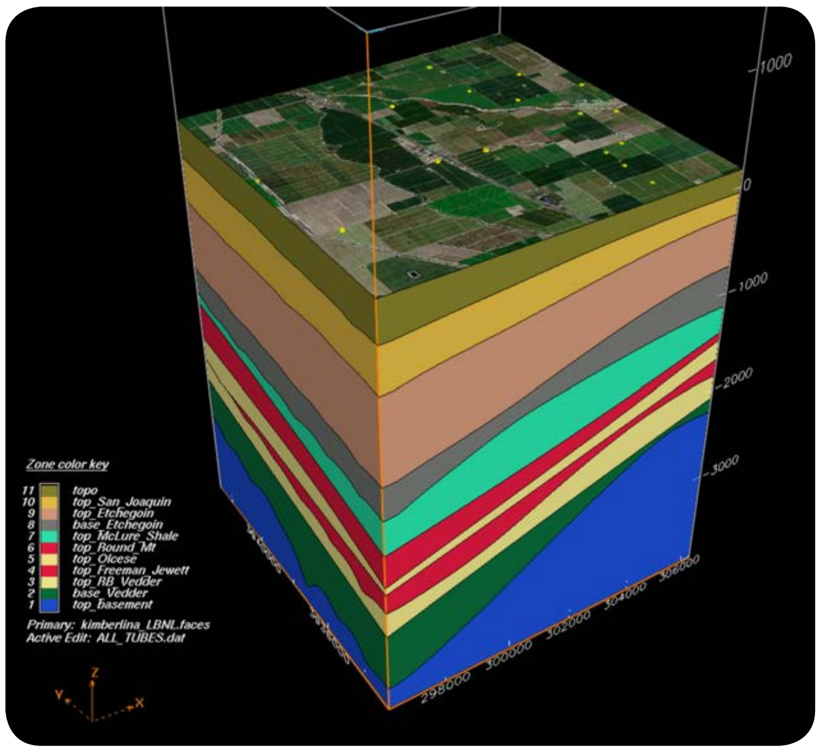
Within the WESTCARB region, California offers a natural focus for CCUS because of its large sedimentary basins, hydrocarbon reservoirs, clusters of large CO_2 stationary sources, and mandatory greenhouse gas reduction regulations.

California's Central Valley, composed of the Sacramento Basin to the north and the San Joaquin Basin to the south, contains the state's largest onshore geologic CO_2 storage resource. WESTCARB has focused its research on these two basins to better characterize their commercial-scale CO_2 storage potential.

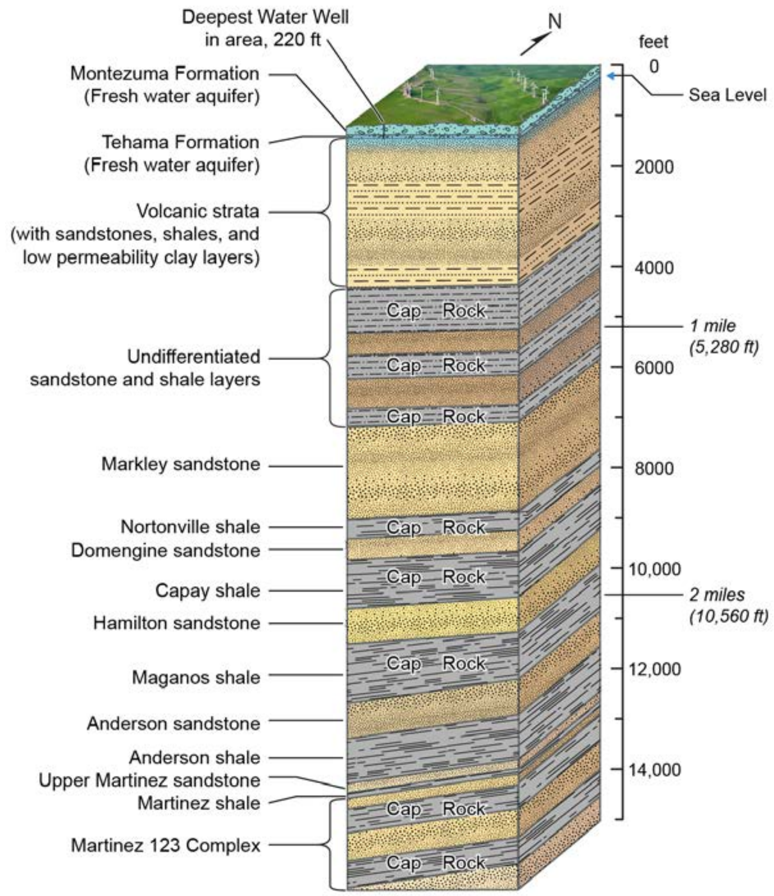
Researchers from the California Geological Survey conducted a preliminary assessment of the Upper Cretaceous Mokelumne River, Starkey, and Winters sandstone formations in the southern Sacramento Basin and found a combined storage resource of 3 billion to 13 billion metric tons (3.5 billion to 14 billion tons) of CO_2. The area is proximal to large industrial facilities in the San Francisco Bay area. In addition, depleting natural gas fields offer the potential for CO_2 enhanced gas recovery and use of existing infrastructure. WESTCARB geologic characterization work in the Montezuma Hills area (Solano County) and a stratigraphic well drilled on King Island (San Joaquin County) are providing data to better define the storage characteristics of major gas-bearing and saline formations.



Natural gas fields in the Sacramento Valley attest to the presence of reservoirs capable of storing CO_2.



Initial geomodel developed by Lawrence Livermore National Laboratory for the formations underlying the Kimberlina study site.



Stratigraphic column developed by Lawrence Berkeley National Laboratory showing the formations underlying the Montezuma Hills study site.

In the southern San Joaquin Valley, WESTCARB conducted initial site characterization work at Clean Energy Systems' Kimberlina oxy-combustion power plant north of Bakersfield. Modelers from Lawrence Livermore National Laboratory constructed a 3-D geomodel, and Lawrence Berkeley National Laboratory researchers simulated the injection of 1 million tons of CO_2 into the Vedder Sandstone, a regionally continuous formation. At Kimberlina, the Vedder is a braided stream unit approximately 150 meters (500 feet) thick, at a depth of approximately 2,400 meters (8,000 feet). Thick shale units provide good overlying seals at the site and surrounding areas.

In addition to saline formations, the southern San Joaquin Valley has 121 oil fields with an estimated storage resource of 3 billion metric tons (3.4 billion tons). Some of these fields are candidates for CO_2-EOR. Oil fields suitable for CO_2-EOR are also located in Ventura County and the Los Angeles Basin (offshore and onshore). As California's greenhouse gas emissions laws take effect, the development of local CO_2 supplies from industrial capture may make recovery of additional oil, combined with CO_2 storage, economically viable.

The Citizen Green Geologic Characterization Well in the Sacramento Basin, California

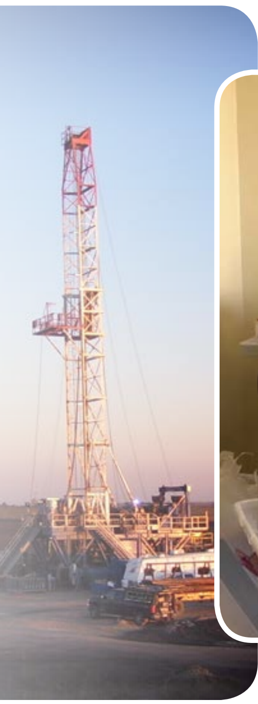
The Central Valley of California, a large depositional basin divided into the Sacramento Basin to the north and the San Joaquin Basin to the south, offers some of the most promising onshore CO_2 storage opportunities in WESTCARB's territory.

In December 2011, WESTCARB drilled a stratigraphic well to characterize the CO_2 storage potential of regionally extensive geologic formations in the southwestern part of the Sacramento Basin. The Citizen Green well, drilled directionally to a vertical depth of 2,110 meters (6,920 feet), reused the pad and surface casing of an existing depleted natural gas well on King Island, an agricultural area near Stockton. The King Island gas field is part of northern California's natural gas producing region and is in close proximity to major industrial and power plant CO_2 sources.

Rock samples and logging data collected from the Citizen Green well are providing information on the CO_2 storage potential of thick sandstone formations and the integrity of the overlying shale units to provide seals. The whole core recovered during drilling included the transition from a deep shale to an underlying sandstone, and another long sample from a deeper sandstone formation that produces natural gas at other locations. In addition, 43 sidewall cores were recovered from three regionally extensive sandstone units. Wireline logging was conducted over a vertical depth of 991 to 2,097 meters (3,250 to 6,880 feet) and provided data on the porosity, permeability, mineralogy, and geomechanical properties of the formations and formation fluids.

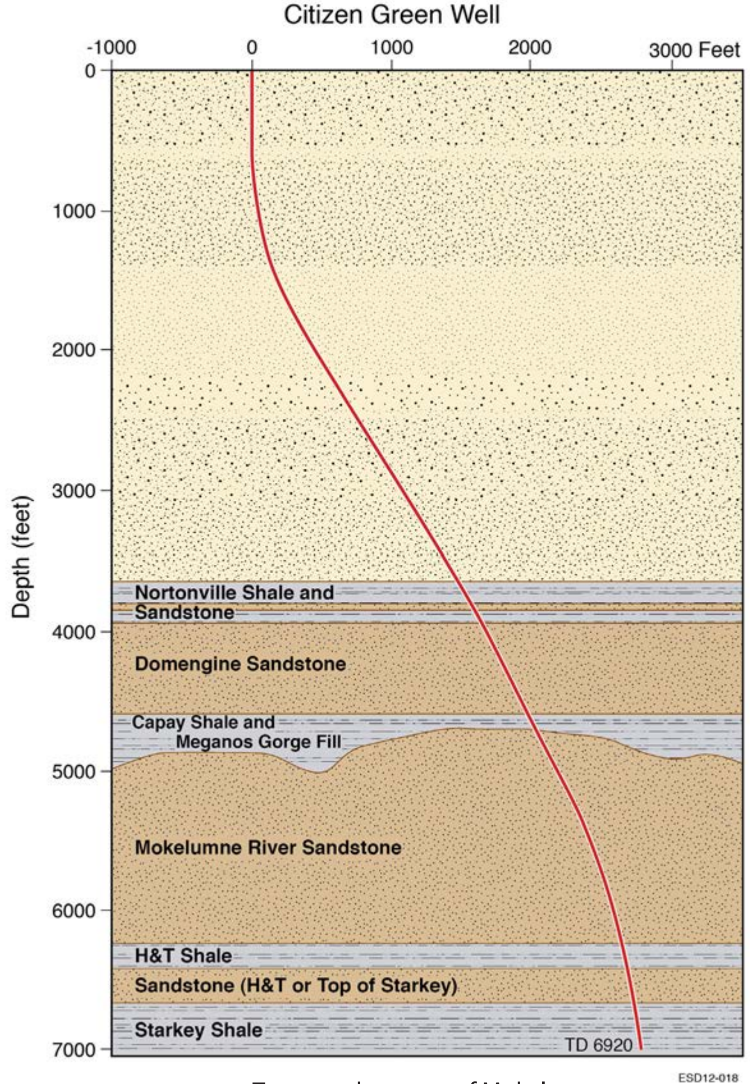
The core samples and logging data are being analyzed at Lawrence Berkeley National Laboratory and shared with researchers at two DOE Frontier Energy Research Centers and several universities. Researchers will first determine the physical, chemical, and biological characteristics of the core samples. Laboratory tests will then evaluate CO_2 injectivity, storage resource, geochemical and biological interactions, multi-phase fluid flow, and trapping mechanisms. The core samples will eventually be archived in the California Well Sample Repository at California State University–Bakersfield, where they will be available for future research.

WESTCARB's characterization work at the King Island site will help the region's CO_2 emitters assess geologic storage options for meeting greenhouse gas reduction obligations, and it may help natural gas producers determine how CO_2 storage could extend the useful life of natural gas fields.



Core barrel retrieval on the drill rig.

Pulling whole core from the core barrel.



Topography at top of Mokelumne River Formation based on 3-D seismic interpretation by T. Fassio.

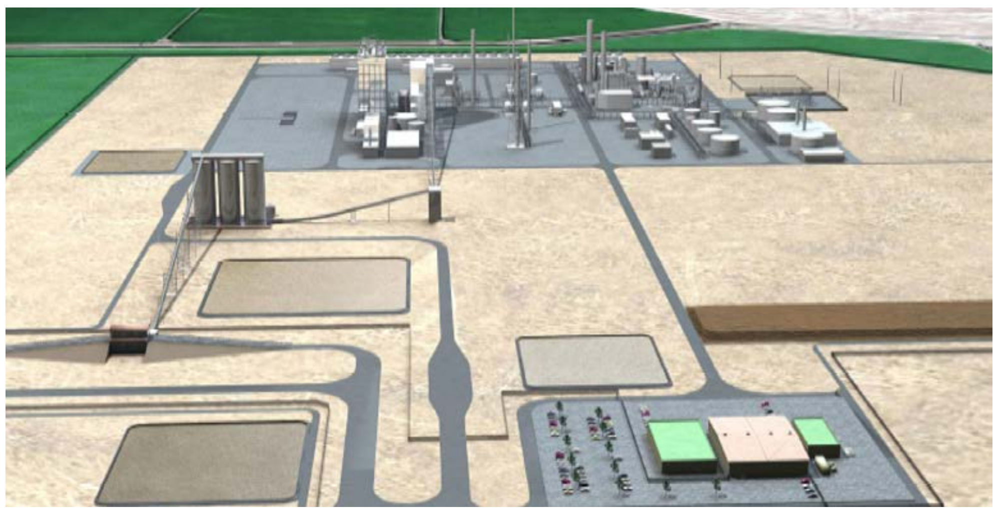
Mudlogger examines chip samples.

Core handling and preservation in the field.

Geochemist measuring core gases.

Jobs and other economic benefits can help CCUS technologies become established in the WESTCARB region.

A turbine departs Seimens' facility for Clean Energy Systems' Kimberlina Power Plant in California, where oxy-combustion technology is being scaled up.



Artist's rendering of HECA's proposed integrated combined cycle power plant in Kern County, California.

Commercializing CCUS in the WESTCARB Region

The WESTCARB region is poised to become an early adopter of CCUS because of state and provincial policies to reduce CO_2 emissions, the general proximity of industrial emission sources to storage-suitable reservoirs, opportunities for economic co-benefits to CO_2 storage from enhanced oil and natural gas recovery, and a concentration of startup companies developing innovative CO_2 "beneficial use" technologies ranging from building materials to biofuels to geothermal energy. The creation and retention of regional jobs are important aspects in developing CO_2 utilization technologies and can help garner public support.

Oil companies have tested CO_2-EOR in California and have candidate projects awaiting the quantities of CO_2 expected from future industrial capture applications. Carbon dioxide-enhanced oil recovery opportunities have also been identified in Alaska. CO_2-enhanced natural gas recovery and the use of CO_2 as a cushion gas for natural gas storage or for compressed air energy storage are less mature technologies that require further field testing and evaluation. The use of CO_2 in geothermal power cycles is also in development and undergoing field validation. Collectively, these technologies could use significant volumes of CO_2 captured at stationary sources in the WESTCARB region.

Novel technologies with the potential to use industrially captured CO_2, such as chemicals or biofuels synthesis and building materials production, can also play an important role in regional greenhouse gas reductions, as well as in meeting other environmental objectives such as air quality improvement, use of "green materials," and reduced solid waste volumes.

Integrated projects have been proposed that combine CO_2 capture, utilization (with associated revenue streams), and residual geologic storage. An example is the Hydrogen Energy California (HECA) project, which will combine an integrated gasification combined cycle power plant with CO_2 capture and urea fertilizer production, allowing for multiple product sales, including CO_2 for EOR in nearby oilfields, with long-term geologic storage at the conclusion of oil-producing operations.

WESTCARB Outreach and Education

WESTCARB promotes dialog on CCUS among the research community, policymakers, industry, tribal and non-governmental organizations, media, and the public. WESTCARB is committed to sharing information and gaining feedback from stakeholders on the diverse aspects of CCUS technology and project development.

WESTCARB works with universities, trade associations, and environmental organizations to conduct public workshops on CCUS. To further CCUS education, WESTCARB supports the Keystone Center's teacher trainings and regional professional development through the Carbon Tech Alliance.

WESTCARB provides technical knowledge sharing to regulators and policymakers interested in including CCUS technologies in greenhouse gas mitigation compliance mechanisms. WESTCARB has organized several CCUS workshops in support of California's biennial Integrated Energy Policy Report, an important guidance document for the state. WESTCARB researchers co-authored the *Geologic Carbon Sequestration Strategies for California: Report to the Legislature* in response to Assembly Bill 1925. In 2010, they served as technical advisors to the California Carbon Capture and Storage Review Panel, which was convened by state agencies to draw up recommendations for CCUS regulation. The Panel issued 12 recommendations addressing key permitting, legal, and socio-economic issues for CCUS in California. A bill that incorporates several of these recommendations has been introduced to the state legislature. In Washington, WESTCARB members contributed to a similar CCUS regulatory development process in 2007–2008.

WESTCARB hosts public meetings in communities where field projects are proposed, and has held its annual business meetings in Alaska, Arizona, California, Oregon, and Washington to encourage participation throughout the region. To give stakeholders a firsthand look at CCUS technologies, WESTCARB arranges tours of project sites.

California Energy Commissioner Jim Boyd visits the Citizen Green well site.

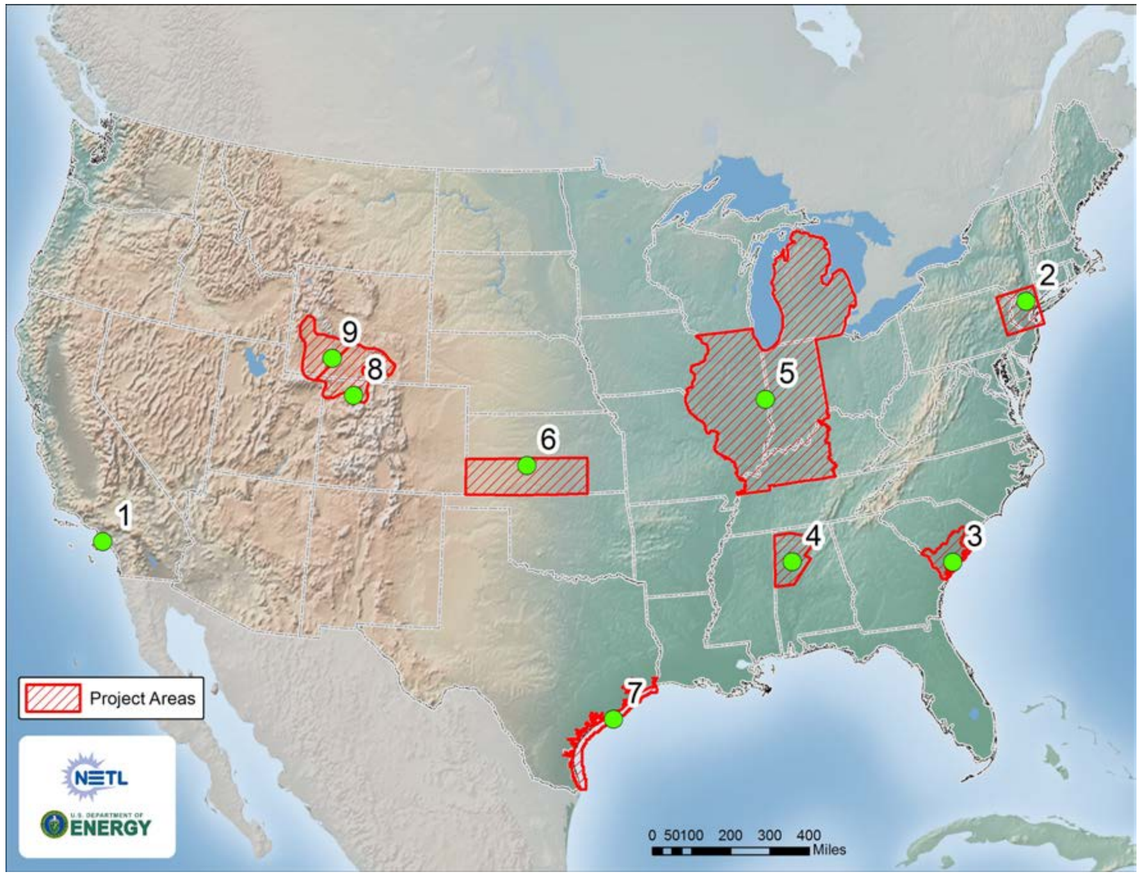
Regular communication with landowners contributes to successful field projects.

WESTCARB participants tour an oxy-combustion power plant.

Attendees at WESTCARB's annual business meeting in Zolo.

An open house provides an opportunity for community members to talk one-on-one with WESTCARB researchers.

Educators participate in a climate change/CCUS teacher training. (Photo courtesy of Wendi Liles, The Keystone Center)



ARRA Site Characterization Projects

The U.S. Department of Energy's National Energy Technology Laboratory has selected and funded several field projects to characterize promising geologic formations for CO_2 storage. The majority of the funding was provided by the American Recovery and Reinvestment Act of 2009 (ARRA). This research further advances DOE's efforts to develop a national assessment of CO_2 storage capacity in deep geologic formations. These projects are providing greater insight into the potential for geologic reservoirs across the United States to safely and permanently store CO_2.

This work focuses on the regional site characterization of high-potential geologic storage formations. Geologic formation types being evaluated include saline formations, active/depleted oil fields (but not specifically or primarily for the purpose of enhanced oil recovery), and unmineable coal seams. The formations selected for characterization possess seals adequate to protect against adverse impacts on the overlying formations and minimize risks to underground sources of drinking water. The projects will develop comprehensive data sets of formation characteristics (porosity, permeability, reservoir architecture, cap rock integrity, etc.)—efforts which represent a small step towards understanding the geology of potential storage formations in the United States.

Each of these projects will contribute to the knowledge base of best practices for site characterization and storage site selection. These projects will also support the development of best practice manuals for regional geologic characterization and participation in "knowledge sharing" within technical working groups.

More information is available on NETL's ARRA Site Characterization webpage located at:

http://www.netl.doe.gov/technologies/carbon_seq/infrastructure/arrasitechar.html.

Key	Participant	Project Title	Characterization Activities
1	**GeoMechanics Technologies**	Characterization of the Pliocene and Miocene Formations in the Wilmington Graben, Offshore Los Angeles, for Large Scale Geologic Storage of CO_2	Off-shore Pliocene and Miocene-age formations, Los Angeles Basin, Wilmington Graben
2	**Sandia Technologies**	Characterization of the Triassic Newark Basin of New York & New Jersey for Geologic Storage of Carbon Dioxide	Triassic to Cambrian-age formations and diabase sills within the Newark Rift Basin
3	**South Carolina Research Foundation**	Geologic Characterization of the South Georgia Rift Basin for Source Proximal CO_2 Storage	Jurassic and Triassic-age formations of the Mesozoic South Georgia Rift Basin
4	**University of Alabama**	Site Characterization for CO_2 Storage from Coal-fired Power Facilities in the Black Warrior Basin of Alabama	Stacked Cambrian through Pennsylvanian saline formations, Black Warrior Basin, Alabama
5	**University of Illinois**	An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins	Cambrian-Ordovician-age Knox Supergroup and St. Peter Sandstone, Illinois and Michigan Basins
6	**University of Kansas Center for Research**	Modeling CO_2 Sequestration in a Saline Aquifer and Depleted Oil Reservoir to Evaluate Regional CO_2 Sequestration Potential of Ozark Plateau Aquifer System, South-Central Kansas	Mississippian-age Chert Formation, Cambrian-Ordovician-age Arbuckle Group, Ozark Plateau
7	**University of Texas at Austin**	Gulf of Mexico Miocene CO_2 Site Characterization Mega Transect	Near-shore Miocene-age formations, State of Texas Submerged Lands
8	**University of Utah**	Characterization of the Most Promising Sequestration Formations in the Rocky Mountain Region	Cretaceous-age Dakota Sandstone, Jurassic-age Entrada and Navajo Sandstones, and the Pennsylvanian-age Weber Sandstone
9	**University of Wyoming**	Site Characterization of the Highest-Priority Geologic Formations for CO_2 Storage in Wyoming	Weber, Tensleep, and Madison formations of the Rock Springs Uplift and Moxa Arch Deep Saline Reservoirs

Characterization of Pliocene and Miocene Formations in the Wilmington Graben, Offshore Los Angeles, for Large-Scale Geologic Storage of CO_2

GeoMechanics Technologies

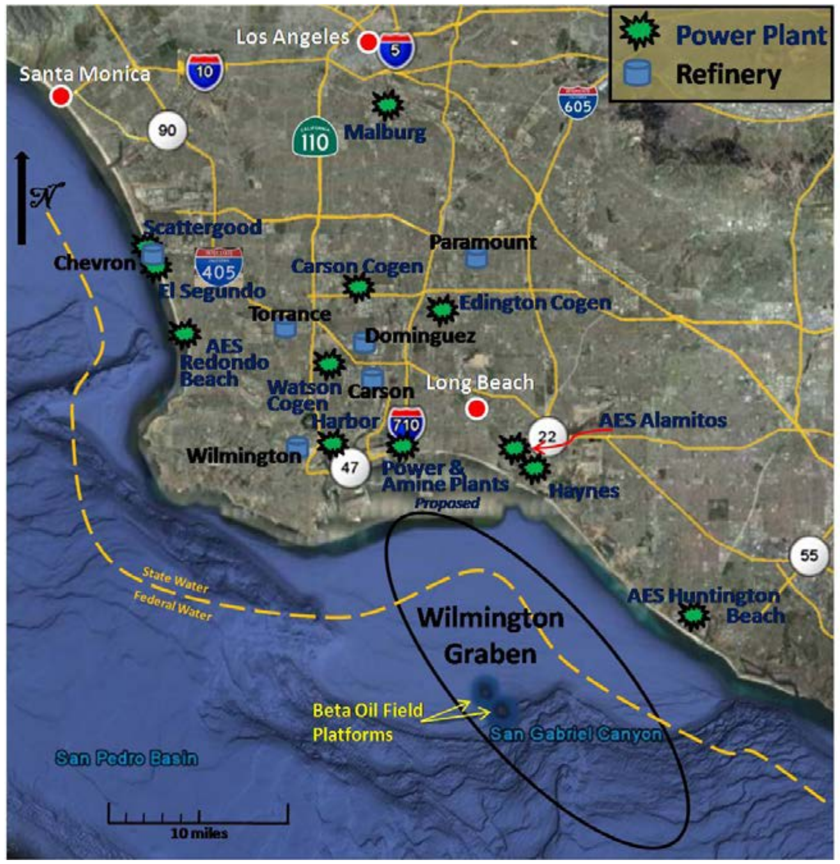
The Los Angeles Basin presents a distinctive combination of high need and significant opportunity for large-scale geologic storage of CO_2. Due to its significant population and historical and geologic setting as one of the most prolific oil and gas producing basins in the United States, the region is home to more than 12 major power plants and oil refineries that produce more than 5 million metric tons of fossil fuel-related CO_2 emissions each year.

GeoMechanics Technologies is characterizing the Pliocene and Miocene sediments in the Wilmington Graben, offshore of Los Angeles, California, for high-volume CO_2 storage. The Graben is located directly offshore in the Los Angeles and Long Beach Harbor area making it easily accessible, yet geologically isolated from the nearby Wilmington oil field and onshore areas. These sediments are expected to span a vertical interval of more than 5,000 feet, with an estimated storage resource of more than 100 million metric tons of CO_2.

The project involves analysis and interpretation of existing geologic data within the region including detailed exploration well log data, and 2-D and 3-D seismic data. New seismic lines have been acquired to fill in current data gap areas, and new characterization wells are being drilled and logged. This information has been integrated with existing geologic interpretations for adjacent onshore areas to help characterize optimal areas for CO_2 storage and seals to safely store CO_2.

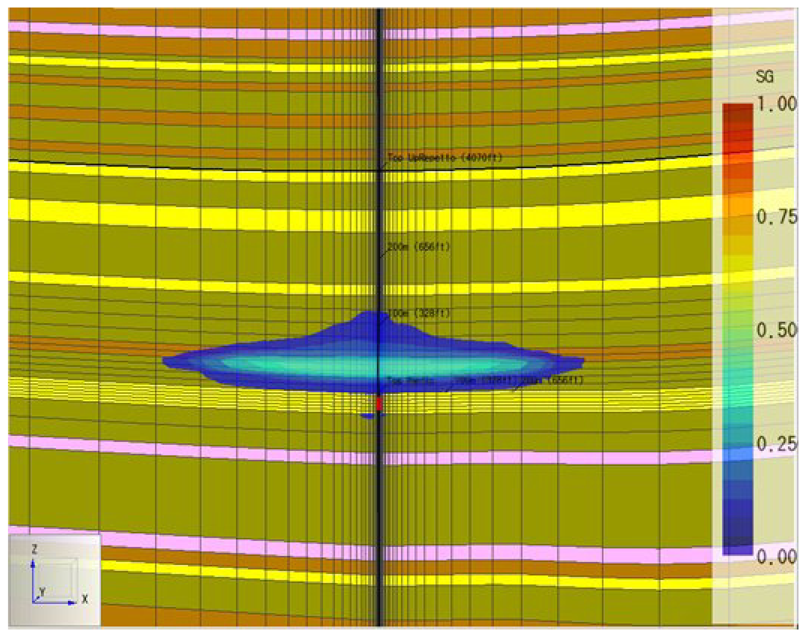
Integrated 3-D geologic and geomechanical models for the Wilmington Graben have been developed to simulate the fate and transport of injected CO_2 in the subsurface and to assess risks.

This project will contribute to the understanding of injectivity, containment mechanisms, rate of dissolution and mineralization, and storage capacity of the Wilmington Graben and associated analog basins. This effort also provides greater insight into the potential for offshore geologic formations of the United States to safely and permanently store CO_2.



Graben location, power plants, and refineries within the geologic Los Angeles Basin.

Drilling site in operation, during pumping and cementing activities.



CO_2-gas saturation after 10 years.

Characterization of the Triassic Newark Basin of New York & New Jersey for Geologic Storage of Carbon Dioxide

Sandia Technologies, LLC

Sandia Technologies, LLC

TriCarb CO_2 Consortium for Carbon Sequestration

Conrad Geoscience Corp. Geologic & Environmental Consultants

Sandia Technologies, LLC, and co-investigator Conrad Geoscience Corporation, are examining the potential for large-scale, permanent storage of CO_2 in deep strata of the Newark Rift Basin. The Newark Rift Basin underlies a heavily industrialized region comprising parts of New York, New Jersey, and Pennsylvania. The primary focus of this project is to examine and confirm the suitability of these Triassic to Cambrian formations for geologic storage of CO_2. The project technical team consists of Columbia University's Lamont Doherty Earth Observatory and Rutgers University scientists, New York State Museum, Schlumberger Carbon Services, and Lawrence Berkeley National Laboratory's Earth Science Division collaborating under the TriCarb Consortium for Carbon Sequestration (www.tricarb.org).

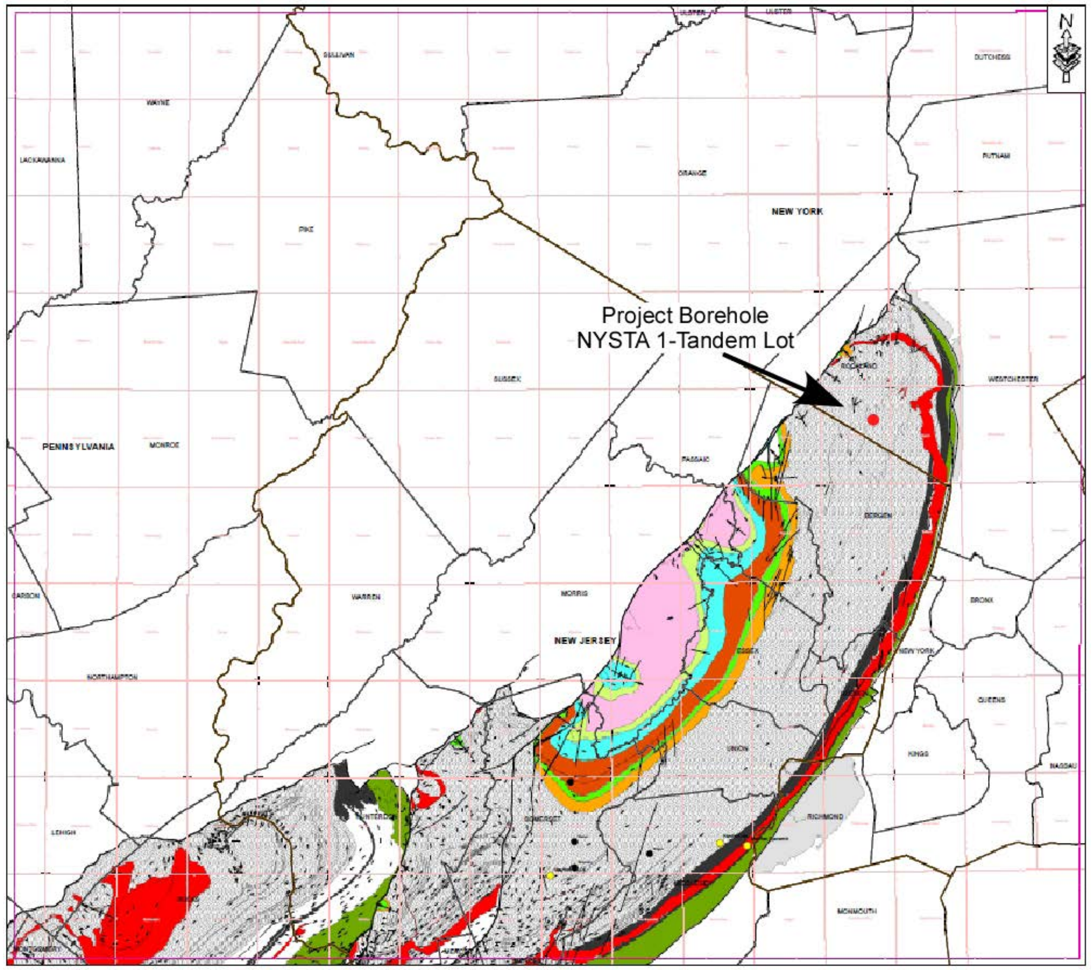
The project objective is to assess the potential for storing large amounts of CO_2 in the geologic formations of the Newark Rift Basin. For example, the Stockton Formation is an extremely promising storage formation within this basin. The project will demonstrate that geologic storage of CO_2 offers an effective and viable large-scale mitigation approach to managing greenhouse gas emissions from industrial sources in the northeastern United States. Project-specific characterization elements consist of 2-D seismic data acquisition across the northern end of the Newark Rift Basin; drilling, logging, and sampling formations in a deep stratigraphic test well; drilling a second shallow (+/- 2,000 feet) stratigraphic test well on the Lamont Doherty Earth Observatory campus.

The stratigraphic test well has been completed, and preliminary geologic and reservoir characterization results indicate Triassic-age lacustrine playa lake and mudbank shales of the Upper Passaic Group will provide an effective seal for the underlying sandstone reservoir layers. This characterization data will be used to further enhance a geochemical signature to define mineral reactions and trapping mechanisms involving CO_2 in the Newark Rift Basin subsurface.

Photo of rig at wellsite.

This project will provide greater insight into the potential for geologic formations across the United States to safely and permanently store CO_2 and contribute to a more precise and thorough understanding of the geologic storage opportunities in the Newark Rift Basin, formation-source matching, and refined storage capacity estimates.

Maps showing the Newark Basin.



Geologic Characterization of the South Georgia Rift Basin for Source Proximal CO_2 Storage

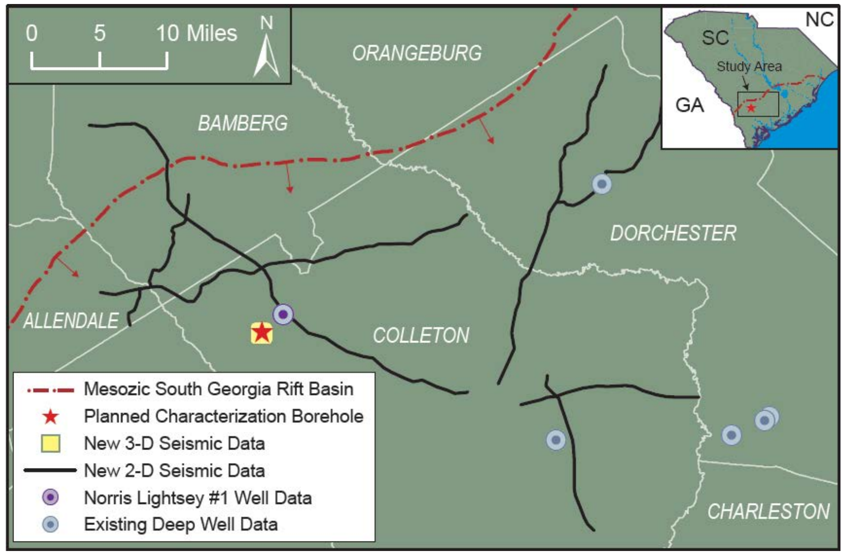
South Carolina Research Foundation

The South Carolina Research Foundation and partners are evaluating the feasibility of CCUS in the Jurassic/Triassic saline formations of the Mesozoic South Georgia Rift Basin, which extends from South Carolina into Georgia. The Jurassic/Triassic sequence, based on preliminary assessment of limited geologic and geophysical data, appears to have both the appropriate areal extent and multiple horizons where significant amounts of CO_2 may potentially be stored permanently and safely. The presence of several igneous rock and sedimentary shale layers within the sequence may provide adequate seals to prevent upward migration of CO_2 into the Coastal Plain formation systems. The Jurassic/Triassic saline formations of the South Georgia Rift have been identified as prospective CO_2 storage areas; however, detailed characterization must be conducted to reduce uncertainties and validate storage potential.

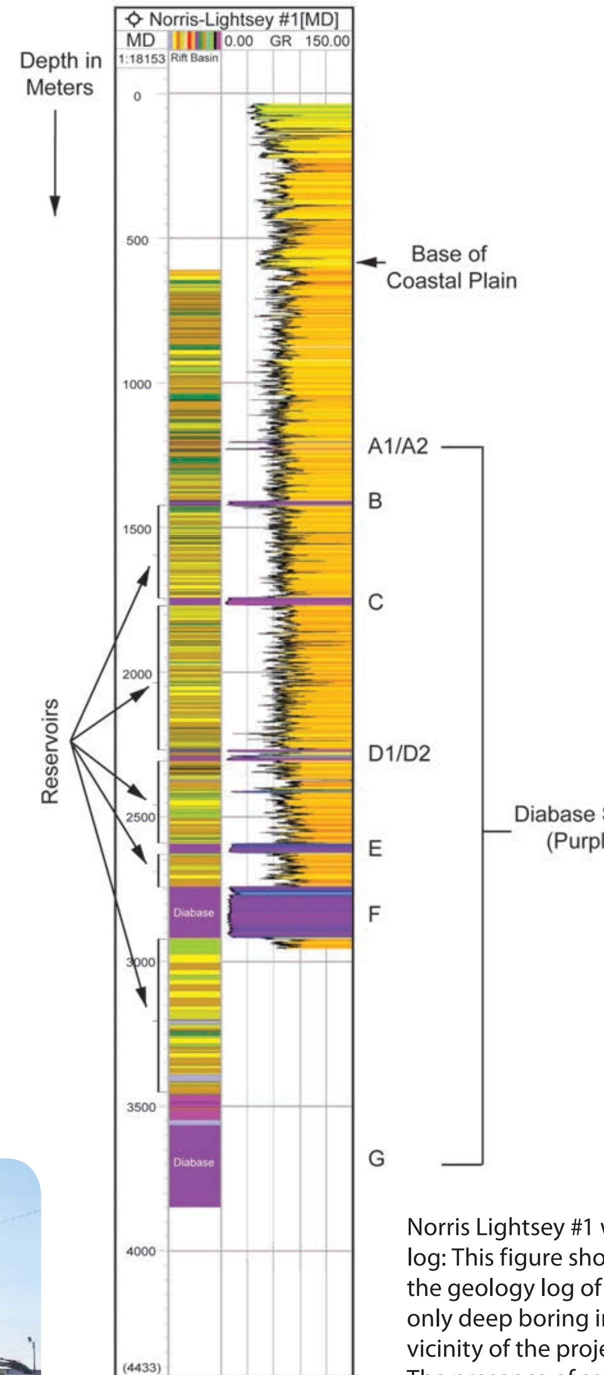
The project will evaluate existing geologic and geophysical data, reprocess historical seismic data, collect additional seismic data to fill in historical data gaps, drill and test a characterization well, and conduct reservoir modeling, a risk assessment, and mitigation studies. The additional seismic and geologic data will be collected in order to fill in any data gaps and used to evaluate faults, fractures, and confining zone integrity for potential release pathways. A primary objective of this study is to use new seismic data combined with the characterization well data to determine if potential trapping reservoirs are structurally competent to contain dense phase CO_2 if injected. The characterization well was drilled to a depth of 6,202 feet and includes a detailed description of the potential reservoirs and seals to determine thickness, lithology, mineralogy, and fracture orientation.

The project team has collected a sizable amount of seismic data throughout the study area. This data has been integrated into a numerical model to simulate the injection and migration of 30 million metric tons of CO_2 in the Jurassic/Triassic sediments of the South Georgia Rift, with layers of diabase (an igneous intrusion) acting as a primary seal.

One of the main benefits of this project is the contribution to the understanding of CO_2 injectivity, containment mechanisms, rate of dissolution and mineralization, and storage capacity of the onshore portion of the South Georgia Rift Basin and associated analog basins.



Project area with locations of existing geologic characterization information that has been collected.



Norris Lightsey #1 well log: This figure shows the geology log of the only deep boring in the vicinity of the project area. The presence of several diabase layers that may act as seals for multiple CO_2 storage reservoirs in a stacked storage concept can be seen in this log.

The 2-D seismic reflection acquisition by Bay Geophysical was collected using three Vibroseis trucks. The picture was taken along line SCO2-5.

Site Characterization for CO_2 Storage from Coal-Fired Power Facilities in the Black Warrior Basin of Alabama

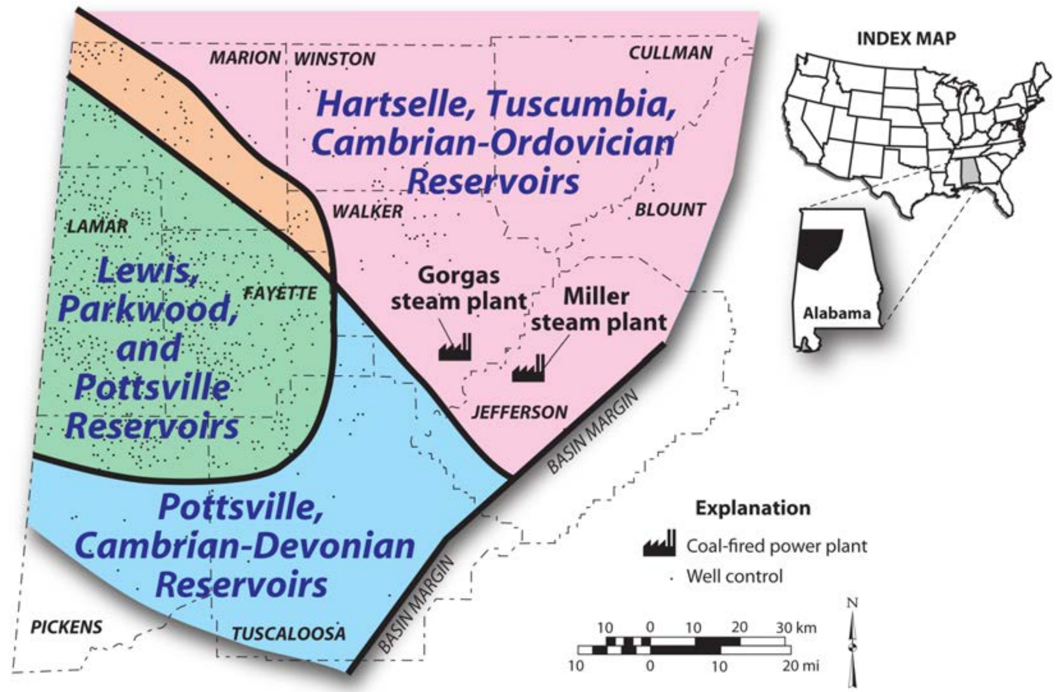
University of Alabama

The Black Warrior Basin of Alabama contains two major coal-fired power plants that serve the Birmingham-Tuscaloosa economic corridor and emit more than 27 million metric tons of CO_2 annually. The basin hosts diverse coal, coalbed methane, and conventional oil and gas resources. The basin also has potential CO_2 storage capacity in an array of sandstone, limestone, and dolostone units of Cambrian through Pennsylvanian age. The University of Alabama, Geological Survey of Alabama, and Rice University are identifying CO_2 storage opportunities in the Black Warrior Basin. Multiple stacked saline formations at depths greater than 2,500 feet that have not yet been characterized underlie two power plants. These saline formations represent potential long-term CO_2 storage, accompanied by enhanced recovery opportunities for mature oil and natural gas fields in the basin. Multiple seals of regional extent protect underground sources of drinking water.

This effort has two primary objectives:
(1) quantify the ability of the saline formations and mature conventional hydrocarbon reservoirs to accept and retain CO_2 and
(2) develop a site characterization, selection, and development plan to facilitate commercial utilization of these formations for CO_2 storage, including opportunities for enhanced oil/gas recovery. Best practices are being identified for site characterization and selection, as well as identifying and quantifying the risks associated with commercialized geologic storage technology in the Black Warrior Basin. Current storage resource estimates indicate that the basin could store approximately 28.2 billion metric tons of CO_2.

The project team has developed a characterization test site (Gorgas #1 well) at the William C. Gorgas Electrical Generating Plant, which is operated by the Alabama Power Company. The Gorgas #1 well has been completed and a suite of geophysical logs has been collected from the wellbore. Several cores were collected from the Paleozoic strata in the subsurface. Acquisition of approximately 10 miles of 2-D seismic in the vicinity of Gorgas Power Plant has been completed, and reservoir simulations have been initiated to refine estimates of storage capacity.

The study is characterizing the ability of the Black Warrior Basin saline formations and hydrocarbon reservoirs to accept and retain significant volumes of CO_2 from stationary emission sources in the region. Additionally, the project will create potential opportunities to employ CO_2 for enhanced oil/gas recovery and identify risks associated with geologic carbon storage.



Regional map showing location of coal-fired power facilities relative to candidate CO_2 formations in the Black Warrior Basin of Alabama.

The William Crawford Gorgas Electrical Generating Plant, which is operated by Alabama Power Company, is one of two major coal-fired power facilities in the Black Warrior Basin of Alabama. The Gorgas #1 borehole was drilled near the power plant to investigate the potential for geologic carbon storage.

Geologist describing core of a sealing shale formation that was recovered from the Gorgas #1 borehole.

An Evaluation of the Carbon Sequestration Potential of the Cambrian-Ordovician Strata of the Illinois and Michigan Basins

University of Illinois

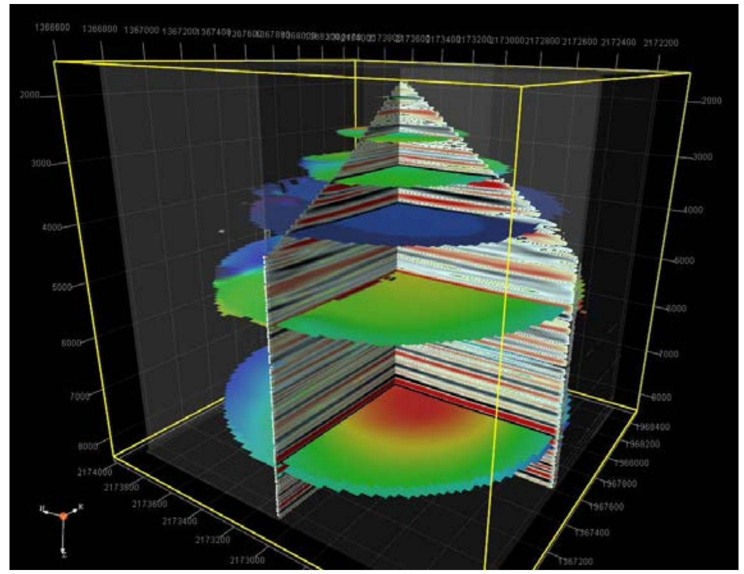
ILLINOIS STATE GEOLOGICAL SURVEY
PRAIRIE RESEARCH INSTITUTE

A consortium including the state geologic surveys of Illinois, Indiana, Kentucky, and Michigan, in collaboration with Brigham Young University, and Schlumberger Carbon Services, is investigating the carbon storage potential of the Cambrian-Ordovician strata that underlie much of Illinois, Indiana, Michigan, and western Kentucky. This research partnership is developing a comprehensive assessment of the CO_2 storage resources within the Midwestern United States to help identify and characterize alternative reservoirs in regions where the underlying Mt. Simon Sandstone may be inadequate for use as a storage reservoir.

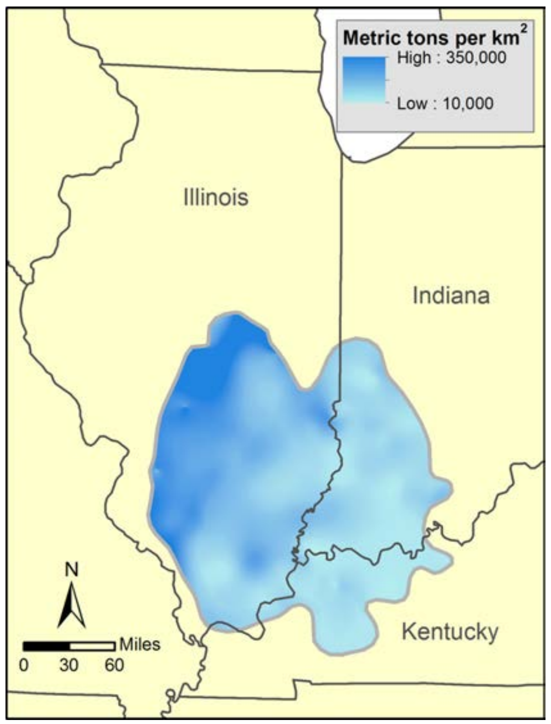
Geologic cross sections have been developed to portray the regional-scale characteristics of the entire Cambrian-Ordovician strata in the Illinois and Michigan Basins. Regional maps have been created to evaluate the geometries of the St. Peter Sandstone and Knox Supergroup units (e.g., Potosi Dolomite/Copper Ridge Group), as well as to examine the primary regional seal (Ordovician Maquoketa Group and Utica Shale) and potential secondary seals. Core samples have been collected for petrophysical analysis from wells in Illinois (ADM Verification Well #1) and Kentucky (Marvin Blan #1), and are providing new detailed information on the reservoirs'pore types and petrophysical properties on both regional and local scales for the entire Cambrian-Ordovician interval. As part of this research, a new database has been developed for analyzing petrophysical results from core analyses and borehole geophysical logs throughout the region, which allows for improved resolution and reduced uncertainty in reservoir quality prediction in areas of high-quality well control. In addition, the development of 3-D geocellular models of stratigraphic units in both the Illinois and Michigan Basins is underway to improve storage capacity estimates by accounting for spatial variability in porosity, permeability, formation pressure, temperature, and salinity.

With a combined thickness exceeding 1,600 feet throughout much of the study area, the St. Peter Sandstone and Knox Supergroup dolomites appear to be promising alternative targets for geologic carbon storage. Estimates for the CO_2 storage resource of the St. Peter Sandstone range from 0.4 to 5.9 billion metric tons in the Illinois Basin and 2.2 to 30 billion metric tons in the Michigan Basin following the methodology outlined in *Atlas III*, Appendix B. Preliminary analysis of the Knox Supergroup suggests that it may provide a very significant storage resource in the Illinois Basin (on par with the Mt. Simon Sandstone) owing to its great thickness in the southern portion of the Basin. Pilot-scale CO_2 injection tests in the Blan well indicate Knox Supergroup dolomites and sandstones are indeed viable carbon storage targets in the southern Illinois Basin.

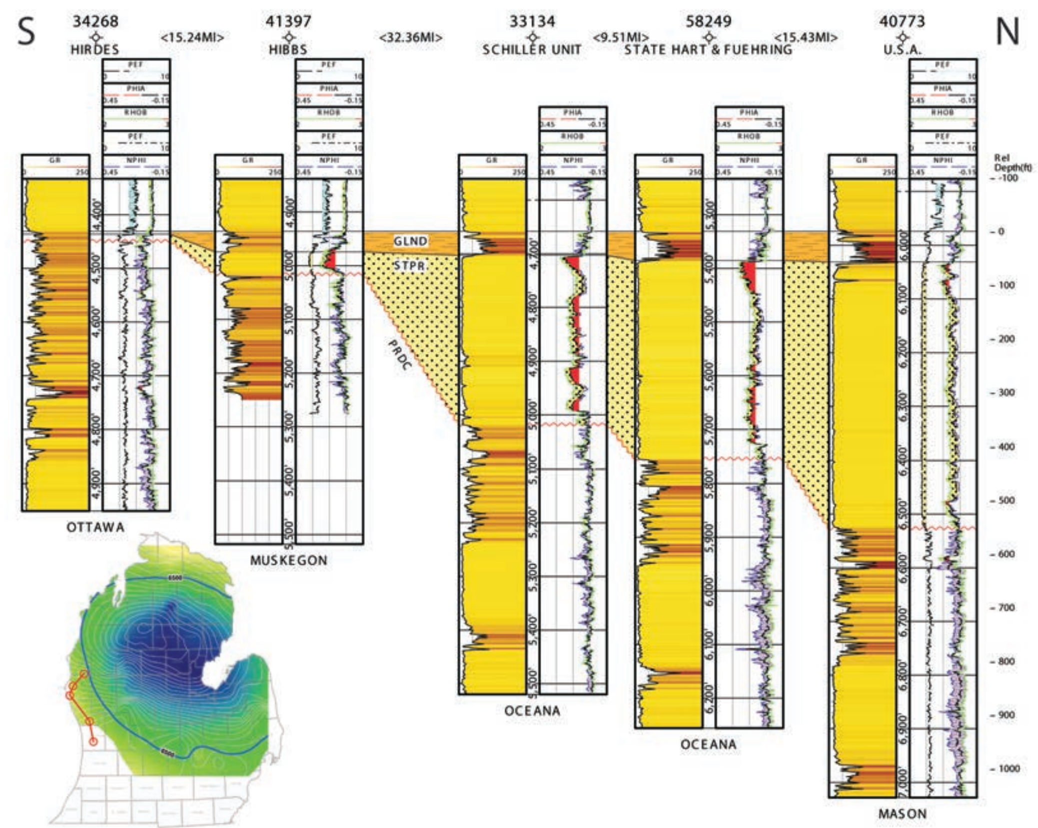
More information is available at the project website: http://knoxstp.org.



Vertical seismic profile from the Hancock County, Kentucky, test site.



Distribution of CO_2 storage resource for the St. Peter Sandstone in the Illinois Basin. Lower salinities may limit the storage resource in the northwest portion of the mapped area.



A south to north stratigraphic cross section of the St. Peter Sandstone in western Lower Michigan showing a 10% porosity cutoff (red highlights in logs), and a stratigraphic pinch-out toward the south. The Glenwood Formation is datum.

Modeling CO_2 Sequestration in a Saline Reservoir and Depleted Oil Reservoir to Evaluate the Regional CO_2 Sequestration Potential of the Ozark Plateau Aquifer System, South-Central Kansas

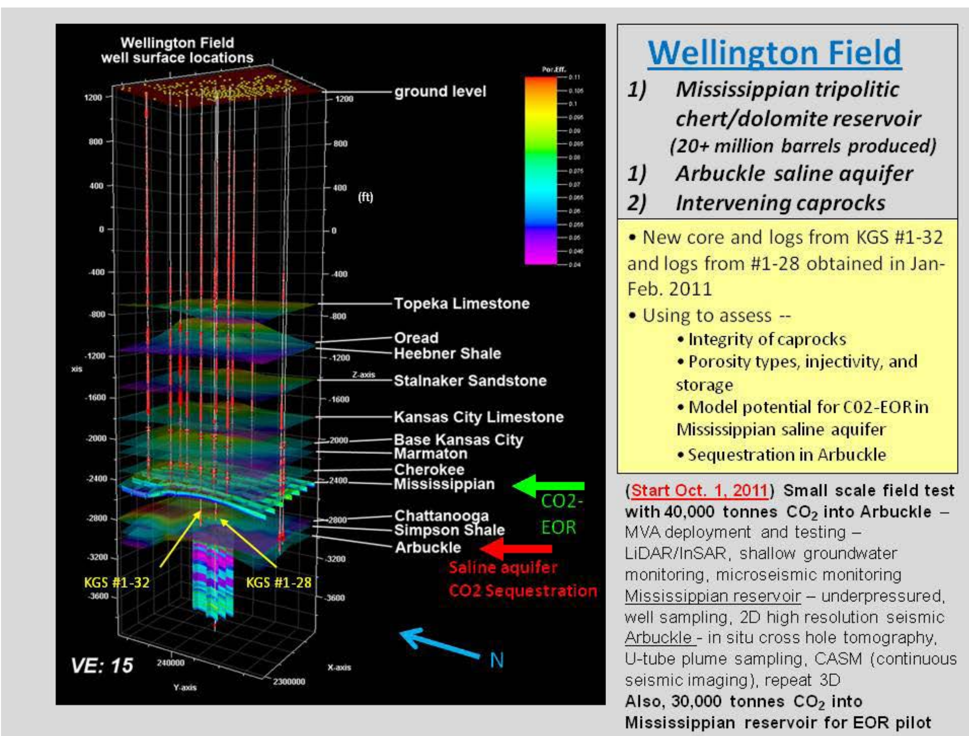
KANSAS GEOLOGICAL SURVEY
The University of Kansas

University of Kansas

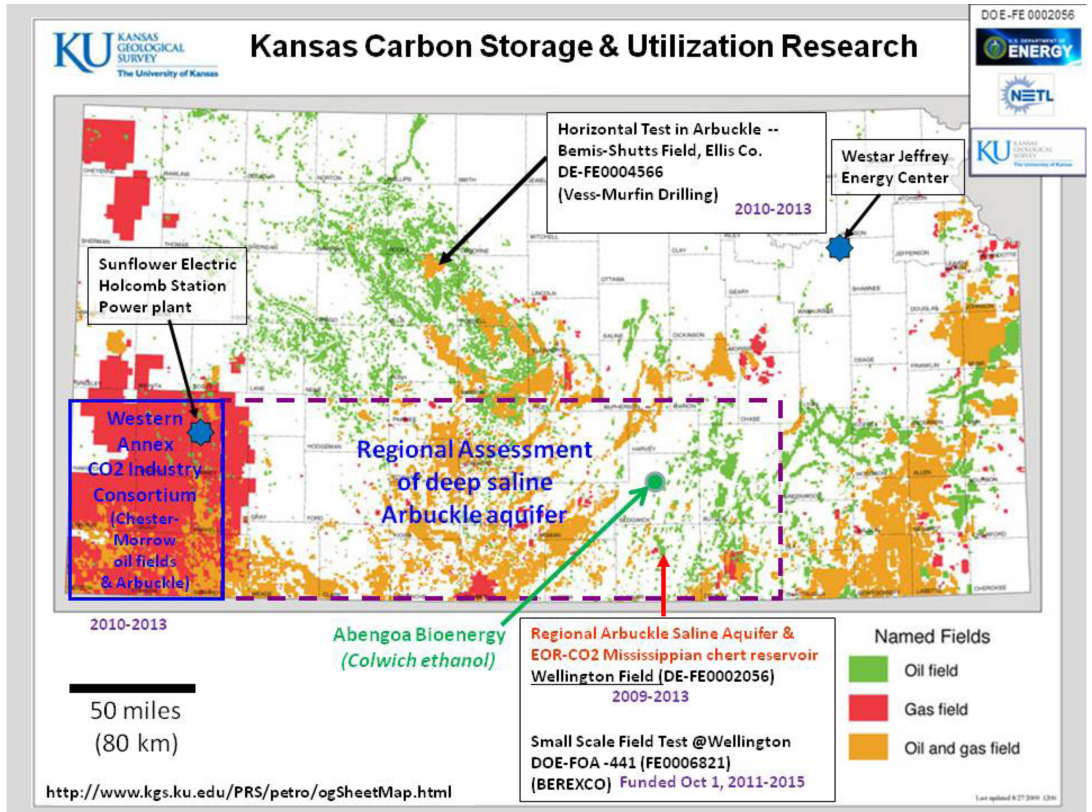
The midcontinent of the United States has a long history of oil exploration and production and a geologic setting that appears to be amenable to the use of CO_2 for enhanced oil recovery (EOR) and long-term storage of CO_2. The Kansas Geological Survey, a division of the University of Kansas, is working with industry and academic partners to study CO_2 storage potential within the Ozark Plateau Aquifer System in south-central Kansas. The study focuses on the Wellington field, with an evaluation of the CO_2-EOR potential of its Mississippian chert formation and the storage potential in the underlying Cambro-Ordovician Arbuckle Group saline formation. A larger study of the Arbuckle Group saline formation is being undertaken over a 33-county area in south-central Kansas to evaluate regional CO_2 storage potential. Additionally, the EOR potential of the Chester and Morrow sandstone formations are being evaluated. This study will demonstrate the integration of seismic, geologic, and engineering approaches to evaluate CO_2 storage potential.

The project is estimating the CO_2 storage potential of multiple formations within the Ozark Plateau Aquifer System by constructing integrated geologic models and performing reservoir simulation studies. The effort involves collecting available historical data, drilling three new wells through the Arbuckle Group, logging the newly drilled wells, coring a portion of the injection and confining zones in two of the new wells, and performing chemical and physical analyses on the samples. Reservoir simulation studies will be conducted to determine CO_2 injectivity in saline formations and calculate the metric tons of CO_2 stored in solution, as well as residual gas saturation and mineral precipitates. These studies will also evaluate the seal integrity needed to overcome the pressure increase from injection, evaluate seal porosity changes due to geochemical reactions, and be used to develop an estimate of potential CO_2 release as a fraction of injection. The modeling results can be used to help predict the fate and transport of CO_2 under an injection scenario and refine overall storage capacity within the Arbuckle. Additionally, the results of this study will help to determine if CO_2-EOR is economically viable for this region.

The project team has acquired seismic, gravity, magnetic, and remote sensing data, drilled two wellbores to completion, recovered and analyzed multiple cores, and analyzed and mapped stratigraphic horizons with CO_2-EOR and storage potential. The team also assessed structural and infrastructure elements that could affect storage permanence and developed models for CO_2 injection and migration analysis.



A three dimensional model of the subsurface of the Wellington field, showing various rock units encountered and locations of existing CO_2-EOR and CO_2 storage projects.



Map showing the location of the projects and oil and gas fields in Kansas.

Gulf of Mexico Miocene CO_2 Site Characterization Mega Transect

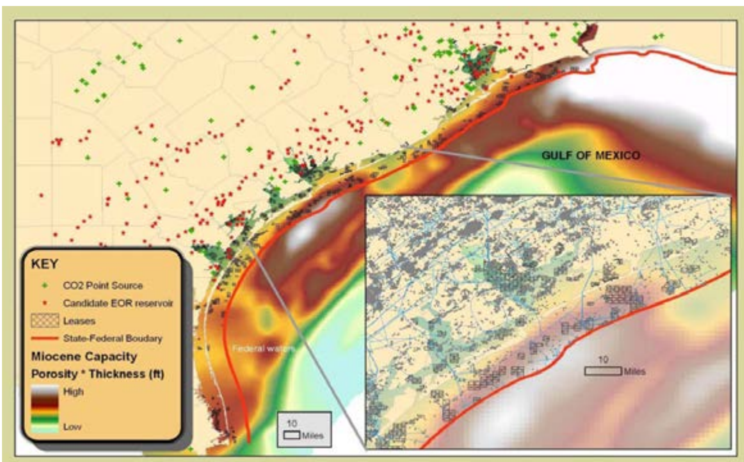
University of Texas at Austin

The University of Texas at Austin and their partners at Los Alamos National Laboratory, Environmental Defense Fund, and Sandia Technologies, LLC, are investigating Texas offshore subsurface storage resources in the Gulf of Mexico as candidate geologic formations for CO_2 storage. This project is identifying one or more CO_2 injection site(s) within an area of Texas offshore state lands (extending 10.3 miles from shore) that are suitable for future large-scale commercial CCUS operations. The objective of the study is to evaluate the Miocene-age geologic section of Texas submerged lands for their ability to permanently store large volumes of anthropogenic CO_2 safely and permanently, as well as to identify at least one site capable of storing a minimum of 30 million metric tons of CO_2.

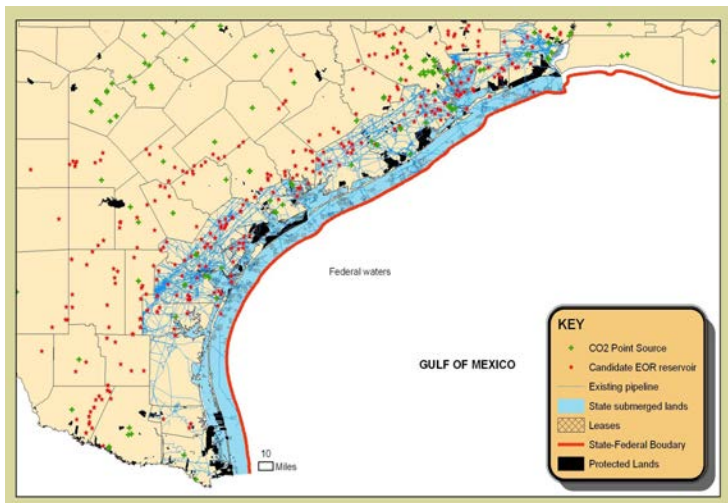
To identify these injection sites, researchers employ both historic and new data to evaluate the candidate geologic formations. Additional work includes evaluating chemical reactions resulting from CO_2 injection into the identified formations and the effects of these reactions on potential commercial-level injection. A risk analysis and mitigation plan is being generated in support of near-term commercial development efforts. In addition to evaluating geologic storage potential of saline aquifers in Miocene formations, the project team is developing a detailed geologic CO_2 storage resource estimate. Initial estimates indicate a storage resource potential of 86 million metric tons of CO_2 within the study area, although this estimate is currently being refined.

The project team has focused on several topics including the procurement and analysis of regional seismic data, petrophysical data and micropaleontologic, fluid and core data from selected wells within the study area. Reservoir, seal, and geochemical suitability (brine and rock-water reactions) are also being investigated. Results to date have suggested a high likelihood for identifying one or more requisite site suitable for CO_2 storage.

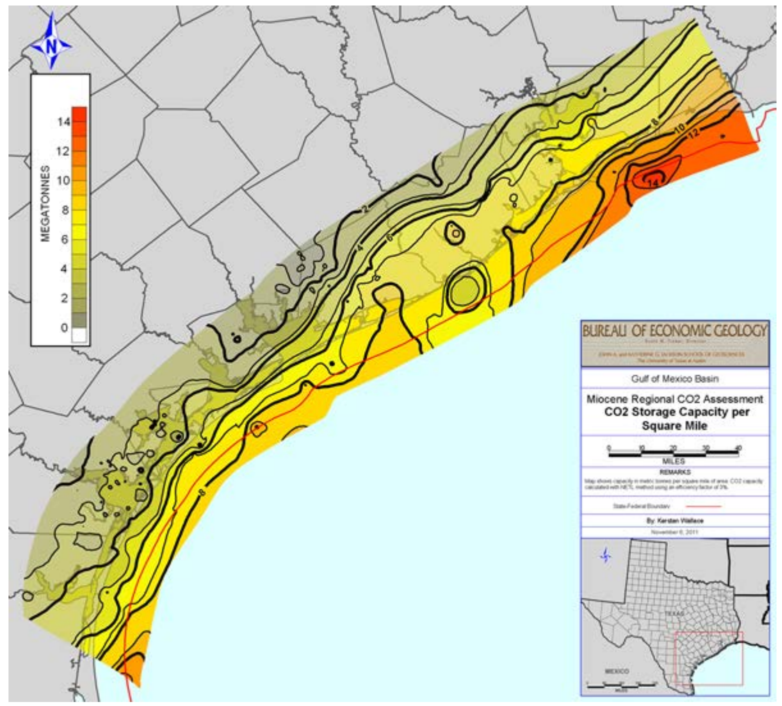
Developing and utilizing offshore geologic storage resources could contribute significantly to the management of CO_2 emissions from various emission sources in southeastern Texas. The University of Texas at Austin has partnered with the General Land Office of Texas, the owner of these offshore lands. This single-owner situation avoids typically troublesome issues for onshore geologic storage projects, such as liability, pore space ownership, and risk to underground sources of drinking water. The results from this study are expected to provide a summary of basin-scale suitability and will identify and prioritize potential offshore CO_2 storage opportunities. Offshore geologic storage may prove to be easier, safer, and less expensive than storing CO_2 in geologic formations on land, particularly during the early days of commercialization.



Miocene porosity and thickness of offshore area to quantify storage potential.



Extent of coastal and offshore study area.



Map of Study area showing capacity (metric tonnes) per square mile of the Miocene age geologic section. Calculated as $GCO_2 = At\ hg\ \Phi t\ \rho CO_2\ Esaline$; where: At = geographical area defining region of CO_2 storage; hg = gross formation thickness; Φt = total porosity; ρCO_2 = density of CO_2 at temperature and pressure of anticipated reservoir conditions; Esaline = CO_2 storage efficiency factor.

Characterization of the Most Promising Sequestration Formations in the Rocky Mountain Region

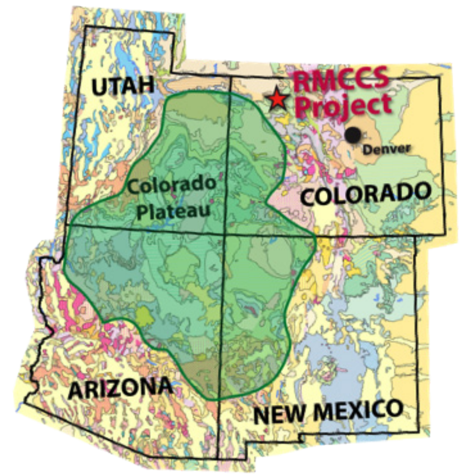
University of Utah

The Rocky Mountain Carbon Capture Sequestration team, led by the University of Utah, has identified the Cretaceous Dakota Sandstone, Jurassic Entrada and Navajo Sandstones, and the Pennsylvanian Weber Sandstone as promising geologic storage formations in the Rocky Mountain region (Colorado Plateau) of the United States. These formations are ubiquitous throughout the region and represent common geologic storage candidate sites for most of the region's stationary CO_2 sources. Most analyses of this project are targeting the Dakota, Entrada, and Weber Sandstones, but meaningful data for the Navajo Sandstone will be included as an ancillary target.

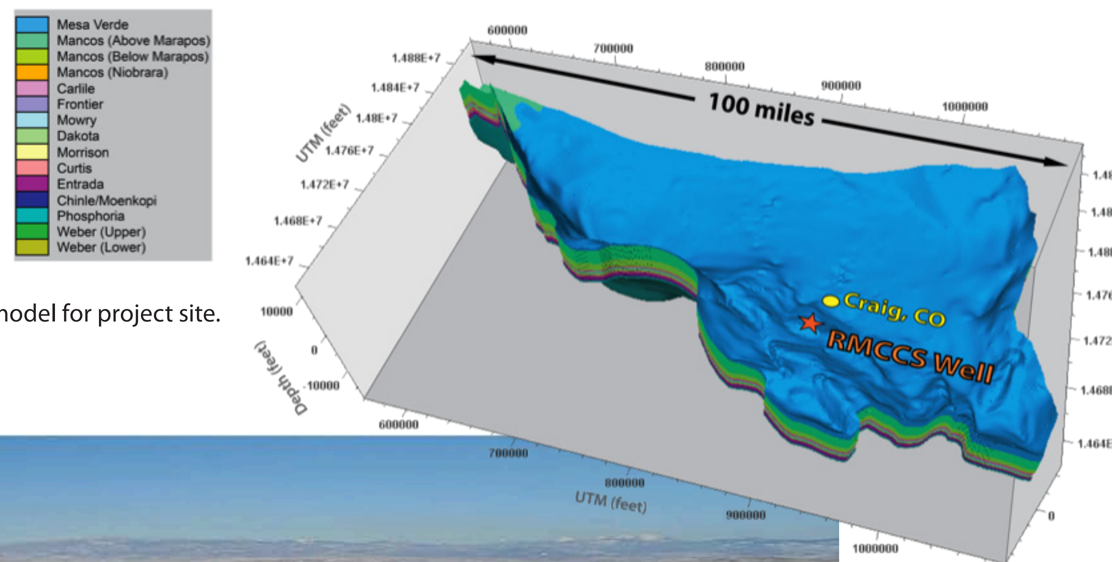
The primary objective of this University of Utah project is to characterize and analyze several of the most promising carbon storage formations near the Craig Power Station in Colorado and similar local case study sites in Arizona, New Mexico, and Utah for potential CCUS activities. The geologic formations of the Rocky Mountain region occur proximally to a majority of the stationary CO_2 sources for the region, which provides a favorable situation for CCUS activities. This project is collecting and analyzing core and geophysical data, as well as collecting new data and analyzing new model simulations for a representative case study near the Craig Power Station. This includes analyzing the storage potential of the deep-saline formations within a large Laramide-age structure. The study includes a detailed structural analysis of this large forced fold, as well as characterization of the finer geologic structure and stratigraphy of the candidate saline formations and their overlying seals. Analyses of the broader region include the Navajo and other promising Jurassic-aged storage formations.

A wellbore was completed in early 2012 for core collection, geophysical logging, and other analyses. Analysis of the core and well logs will consist of detailed geologic and petrophysical parameters. Simulation models were developed and are being implemented to integrate and evaluate CO_2 injectivity and overall capacity potential. Using local information, coupled with data and collaborative support from the geologic surveys of New Mexico, Arizona, Utah, and Colorado, researchers are calibrating broader analyses and extrapolating the regional significance of the target formations in the southwestern United States.

Early simulation results have provided an estimate of the CO_2 capacity for the region around the Craig Power Station (Sand Wash Basin); these values will be further refined as regional well logs are correlated to core collected from the Rocky Mountain Carbon Capture Sequestration well. Current storage resource estimates indicate that more than 700,000 million metric tons of CO_2 could be stored in the saline formations of the southwestern United States. Results from this project are being used to further characterize the regional significance of these formations for the southwestern and central Rocky Mountain region of the United States.



Regional map with project location.



Geologic model for project site.

Project site in wide angle view.

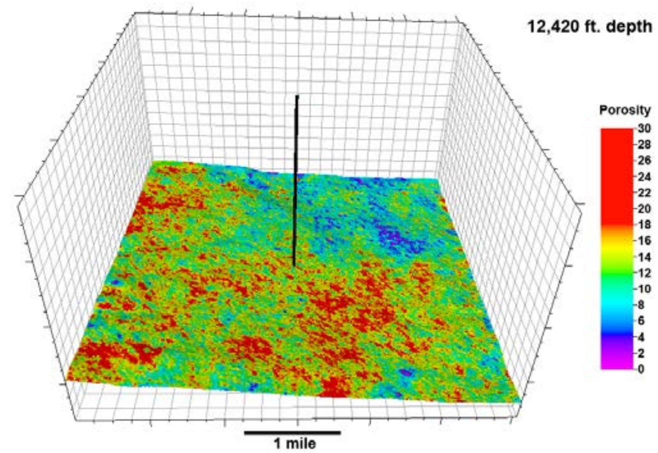
Site Characterization of the Highest Priority Geologic Formations for CO_2 Storage in Wyoming

University of Wyoming

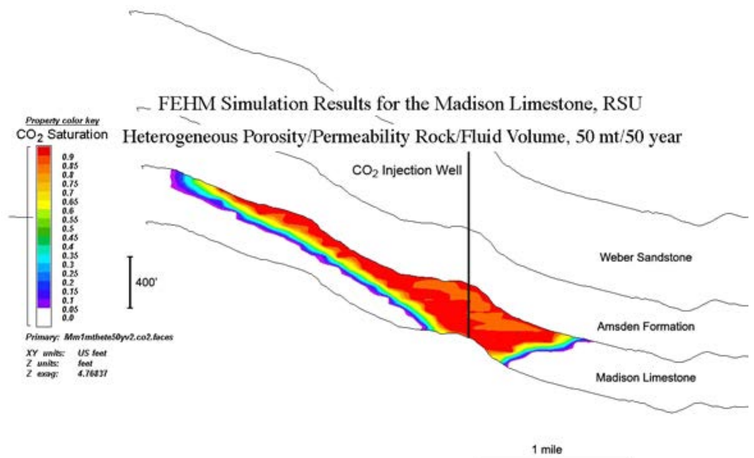
The Wyoming Carbon Underground Storage Project (WY-CUSP) performs site characterization and evaluation, focusing primarily on Wyoming's most promising CO_2 storage formations (the Pennsylvanian Weber/Tensleep Sandstone and Mississippian Madison Limestone) and premier CO_2 storage site (Rock Springs Uplift). Results from both the FutureGen and USGS diagnostic protocols for evaluating CO_2 storage capacity suggest that the two reservoirs on the Rock Springs Uplift could together store approximately 26 billion tons of CO_2.

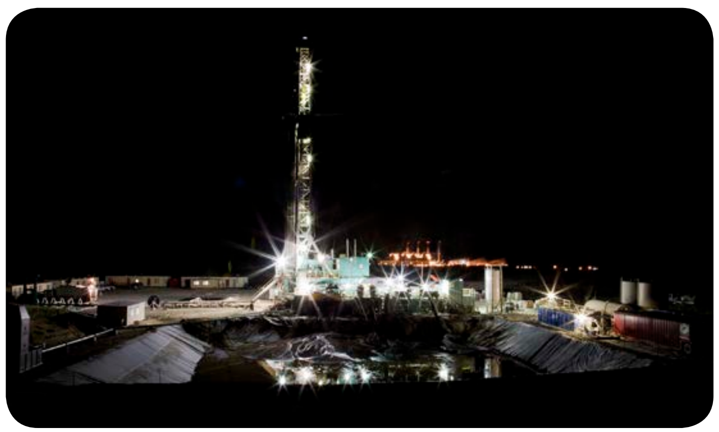
In 2011, the WY-CUSP team drilled a stratigraphic test well and acquired a 25-square-mile 3-D seismic survey for the Rock Springs Uplift site. The drilling was successful: 916 feet of core was retrieved from the 12,810-foot-deep well, along with a complete log suite, borehole images, fluid samples, and other data. Project partners are providing continuous visual documentation of the core, including grain size, mineralogy, facies distribution, and porosity; performing continuous permeability and velocity scans of selected reservoir intervals; and chemically analyzing the fluid samples. WY-CUSP scientists integrated seismic attributes with observations from log suites, a vertical seismic profile survey, core, fluid samples, and laboratory analyses, including continuous permeability scans. From these integrations, researchers constructed 3-D spatial distribution volumes of reservoir and seal properties that more accurately represent geologic heterogeneity at the targeted CO_2 storage site. The WY-CUSP team used this data to perform new CO_2 plume migration simulations. Compared with early simulations derived from homogenous volumes in which plumes are cylindrical with few marginal irregularities, the new simulations produce plumes that occupy larger up-dip rock/fluid volumes and display pronounced marginal irregularities. These irregularities denote zones of higher porosity and permeability, such as collapsed breccias associated with karst zones and/or dolomitized zones in the Madison Limestone.

Currently, only one piece of data is missing from a complete characterization of the reservoir intervals—a measurement of in situ injectivity. As part of the WY-CUSP program, Baker Hughes will prepare the well bore for a series of small-scale water injectivity tests, and the WY-CUSP team will use core intervals to run a series of laboratory injectivity tests with both water and CO_2. These laboratory tests will allow researchers to calibrate the water and CO_2 injectivity tests. Finally, Baker Hughes will hang geophones and convert the test well to a microseismic monitoring well to complete field operations for the project.



Porosity distribution of the Madison Limestone at 12,400 feet below ground surface on the Rock Springs Uplift, Wyoming. The vertical black line in the center of the slice (dimensions are 5 miles by 5 miles) denotes the location of the stratigraphic test well.





The rig used to drill the nearly 13,000-foot-deep Wyoming Carbon Underground Storage Project stratigraphic test well on the Rock Springs Uplift.

Appendix A: Summary of Methodology for Determining Stationary CO_2 Source Emissions

DOE's RCSPs have identified 4,245 CO_2 stationary sources with total annual emissions of more than 3,279 million metric tons of CO_2. These sources include electricity generating plants, ethanol plants, petroleum and natural gas processing facilities, cement plants, agricultural processing facilities, industrial facilities, refineries and chemical plants, fertilizer producing facilities, and unclassified. Estimates were derived using databases and emissions factors, as listed in tables in the methodology.

The full methodology lists the documents used to identify each CO_2 stationary source, as well as the practical quantitative method (i.e., emission factors, continuous emissions-monitoring results, emission estimate equations, etc.) used to estimate CO_2 emissions from that source. In addition, the data sources used to determine specific plant capacities, production outputs, or fuel usage data are listed by RCSP. The full methodology, titled, "CO_2 Stationary Source Emission Estimation Methodologies Summary," is available at: http://www.netl.doe.gov/technologies/carbon_seq/natcarb/co2-stationary-source-emission-estimation-june2010.pdf.

These methodologies were determined by identifying CO_2 stationary sources within each RCSP region, and then assessing the availability of CO_2 emission data or applying an estimate of the CO_2 emissions based upon sound scientific and engineering principles. In each RCSP, emissions were grouped by source and a methodology was established for each emission source industry sector; then the methodology was utilized to estimate the CO_2 emissions from each emission source industry sector. Nine tables containing CO_2 emission estimation methodologies and equations for the major CO_2 stationary source industries summarize these efforts. During the RCSPs' characterization activities, each RCSP developed GHG emission inventories and stationary source surveys within their respective boundary area.

Carbon dioxide stationary sources are categorized according to industry sectors. The table identifies the stationary sources included in various industry sectors.

The RCSPs employed CO_2 emissions estimate methodologies based on the most readily available representative data for each particular industry sector within the respective RCSP area. CO_2 emissions data from databases (for example, EPA's 2010 Greenhouse Gas Emissions from Large Facilities database, eGRID, or ECOFYS) were the first choice for all of the RCSPs, both for identifying major CO_2 stationary sources and for providing reliable emissions estimations. Databases contain reliable and accurate data obtained from direct emissions measurements via continuous

CO_2 Stationary Source Emission Estimation Methodologies Summary

The complete methodology used in the development of CO_2 emissions estimates is available at:

http://www.netl.doe.gov/technologies/carbon_seq/natcarb/co2-stationary-source-emission-estimation-june2010.pdf.

emissions monitoring systems. When databases were not available, CO_2 stationary source facility production or fuel usage data were coupled with CO_2 emissions. Emissions factors, fuel usage data, and facility production data were obtained from various databases, websites, and publications. Carbon dioxide stationary source spatial location data (latitude and longitude) were determined from a variety of sources. Some databases (eGRID) contain latitude and longitude information for each CO_2 stationary source. Where spatial location information was not available through an emissions database, other spatial location methods were utilized. These include the use of mapping tools (Google Earth™, TerraServer, and USGS Digital Orthophoto Imagery) equipped with geospatially defined data, along with web-based databases (Travelpost) containing latitude and longitude information for various U.S. locations.

A summary of the CO_2 stationary source emissions calculated and compiled by each RCSP appears in the "National Perspectives" section of *Atlas IV*. Regional details of these CO_2 stationary source emissions appear in the "Regional Carbon Sequestration Partnerships Perspectives" section of *Atlas IV*. Finally, a state summary of CO_2 stationary source emissions appears in Appendix D of *Atlas IV*.

CO_2 Stationary Sources by Industry Category

Industry Type	CO_2 Stationary Sources Include
Electric Generating Plants	• Coal-, Oil-, and Natural Gas-Fired Power Plants
Ethanol Production Plants	• Ethanol Plants, Regardless of Feedstock Type
Agricultural Processing Facilities	• Sugar Production
Natural Gas Processing Facilities	• Natural Gas Processing Facilities
Industrial Facilities	• Aluminum Production Facilities • Soda Ash Production Facilities • Glass Manufacturing Facilities • Automobile Manufacturing Facilities • Iron Ore Processing Facilities • Compressor Stations • Paper and Pulp Mills
Iron and Steel Facilities	• Iron and Steel Producing Facilities
Cement and Lime Plants	• Lime Production Facilities • Cement Plants
Refineries and Chemical Facilities	• Petroleum Refinery Processing • Ethylene Production Facilities • Ethylene Oxide Production • Hydrogen Production Facilities
Fertilizer Production	• Ammonia Production

Appendix B: Summary of Methodologies Used to Estimate CO_2 Storage Resource

The methodologies derived for estimating geologic storage potential for CO_2 consist of widely accepted assumptions about in-situ fluid distributions in porous formations and fluid displacement processes commonly applied in the petroleum and groundwater science fields. The volumetric approach is the basis for CO_2 resource calculations for all three geologic storage formations. The methods require the area of the target formation or horizon along with the formation's thickness and porosity. There are other specific parameters unique to oil & gas fields and coal seams that are needed to compute the estimated CO_2 storage resource. Because not all of the pore space within any given geologic formation will be available or amenable to CO_2, a storage coefficient (referred to as the efficiency- or E-factor) is applied to the theoretical maximum volume in an effort to determine what fraction of the pore space can effectively store CO_2.

Efficiency is the multiplicative combination of volumetric parameters that reflect the portion of a basin's or region's total pore volume that CO_2 is expected to contact. For example, the CO_2 storage efficiency factor for saline formations (E_{saline}) has several components that reflect different physical barriers that inhibit CO_2 from contacting 100 percent of the pore volume of a given basin or region.

Ranges of values for the E-factor have been calculated for deep saline formations from statistical approaches that consider the variation in geologic properties encountered in subsurface target formations. For the three primary formation types (saline formations, oil and gas reservoirs, and unmineable coal), the full methodology, titled, "Summary of the Methodology for Development of Geologic Storage Estimates for Carbon Dioxide," is available at: http://www.netl.doe.gov/technologies/carbon_seq/natcarb/geologic-storage-estimates-for-carbon-dioxide-sept2010.pdf. The E-factor values for a particular injection horizon can be modified if more specific information about the formation is known, resulting in more precise resource estimations. In situations where this approach is taken, additional metadata is included in NATCARB to explain why the default numbers were not employed.

Summary of the Methodology for Development of Geologic Storage Estimates for Carbon Dioxide

The complete methodology used in the development of CO_2 storage resource estimates is available at:

http://www.netl.doe.gov/technologies/carbon_seq/natcarb/geologic-storage-estimates-for-carbon-dioxide-sept2010.pdf

Carbon Dioxide Storage Resource Estimate Calculation Summary

A CO_2 resource estimate is defined as the volume of porous and permeable sedimentary rocks available for CO_2 storage and accessible to injected CO_2 via drilled and completed wellbores. Carbon dioxide resource assessments do not include economic or regulatory constraints; only physical constraints to define the accessible part of the subsurface are applied. In the following equations, the symbol G_{CO2} refers to the mass of CO_2 that would be stored in the respective geologic medium, A refers to area, and h refers to thickness. The following are brief descriptions of the formulas used in calculating CO_2 storage resource estimations.

Computing CO_2 Resource Estimate – Oil and Gas Reservoirs. The general form of the volumetric equation being used for oil and gas reservoirs in this assessment is as follows:

$$G_{CO2} = A\, h_n\, f_e\, (1\text{-}S_w) B\, \rho\, E_{oil/gas} \quad \text{[Eq. 1]}$$

The reservoir area (*A*), its net thickness (h_n), and its average effective porosity (f_e) terms account for the total volume of pore space. The oil and gas saturation (1-water saturation as a fraction [S_w]) and formation volume factor (*B*) terms account for the pore volume available for CO_2 storage, and CO_2 density (ρ) transforms the pore volume into mass at the reservoir in-situ conditions of temperature and pressure. The CO_2 storage efficiency factor ($E_{oil/gas}$) reflects the fraction of the total pore volume of the oil or gas reservoir that can be filled by CO_2. An efficiency factor is derived from local experience or reservoir simulations.

Computing CO_2 Resource Estimate – Saline Formations. The volumetric equation for CO_2 storage resource estimate potential in saline formations is as follows:

$$G_{CO2} = A_t\, h_g\, f_{tot}\, \rho E_{saline} \quad \text{[Eq. 2]}$$

The total area (A_t), gross formation thickness (h_g), and total porosity (f_{tot}) terms account for the total volume of pore space available. The CO_2 density (ρ) term transforms pore volume into the CO_2 mass that can fit into the formation volume at in-situ conditions of temperature and pressure. The storage efficiency factor (E_{saline}) reflects the fraction of the total pore volume of the saline formation that will be occupied by the injected CO_2. E_{saline} factors for the P_{10}, P_{50}, and P_{90} percent confidence intervals are 0.51 percent, 2.0 percent, and 5.5 percent, respectively.

Computing CO_2 Resource Estimate – Unmineable Coal. The volumetric equation for CO_2 storage resource estimate potential in unmineable coal is as follows:

$$G_{CO2} = A\, h_g\, C_s\, r_{s,max}\, E_{coal} \quad \text{[Eq. 3]}$$

The total area (*A*) and gross seam thickness (h_g) terms account for the total volume of coal available. The fraction of adsorbed CO_2 (C_s) and CO_2 density ($r_{s,max}$) terms account for the mass of CO_2 that would be stored by adsorption in the respective volume of coal at maximum CO_2 saturation. The term *Cs* must consider coal density, CO_2 adsorption capacity (volume of CO_2 adsorbed per unit of coal mass) and coal moisture and ash content. The density of CO_2 in Eq. 3 is that at standard conditions of temperature and pressure ($\rho_{s,max} = 1.87\ kg/m^3$). The storage efficiency factor (E_{coal}) reflects the fraction of the total pore volume that will be occupied by the injected CO_2. E_{coal} factors for the P_{10}, P_{50}, and P_{90} percent confidence intervals are 21 percent, 37 percent, and 48 percent, respectively.

The assessments presented are intended to identify the general geographical distribution of CO_2 storage resources. The assessments are not intended to provide site-specific information for a company to select a site to build a new power plant or to drill a well. This resource estimation is volumetrically based on physically accessible CO_2 storage in specific formations in sedimentary basins without consideration of injection rates, regulations, economics, or surface land usage.

A summary of the national CO_2 storage resource estimates computed by each RCSP ARRA Site Characterization project and compiled by NATCARB appears in the "National Perspectives" section of *Atlas IV*. Regional details of those CO_2 storage resource estimates appear in the "Regional Carbon Sequestration Partnership Perspectives" and "ARRA Site Characterization" sections of *Atlas IV*. A state summary of CO_2 storage resource estimates appears in Appendix D of *Atlas IV*.

Appendix C: Comparison of Publicly Available Methodologies for Development of Geologic Storage Estimates for Carbon Dioxide in Saline Formations

High-level estimates of CO_2 storage resource at the national-, regional-, and basin-scale are required to assess the potential for CCUS technologies to reduce CO_2 emissions for application to saline formations. Carbon dioxide storage resource estimates help to identify potential regions in which CCUS technologies may be successfully implemented. Initiatives for assessing CO_2 geologic storage potential have been conducted since 1993. These initiatives vary from an overview description of assessment tools to a detailed, comprehensive methodology. Although dependable high-level CO_2 storage estimates are essential to ensure successful deployment of CCUS technologies, it is difficult to assess the differences of these estimates without knowing how the current methodologies targeted at high-level CO_2 storage resource estimates for saline formations compare to one another.

High-level CO_2 methodologies for development of geologic storage estimates for CO_2 in saline formations are compared here to assess the differences associated with various methodologies. Six publicly-available, transparent methodologies are applied to 13 saline formation data sets. The data set by Szulczewski, 2012 provides detailed input parameters regarding 13 saline formations (Szulczewski et al., 2012). This data set has been peer-reviewed and is readily available to the public. The methodologies applied to these 13 formations include:

(1) and (2) U.S. DOE Methodology for the Development of Geologic Storage Potential for Carbon Dioxide at the National and Regional Scale (DOE-NETL, 2006, 2008, 2010; Goodman et al., 2011)

(3) CO_2 Storage Capacity Estimation: Methodology and Gaps (Bachu et al., 2007)

(4) A Probabilistic Assessment Methodology for the Evaluation of Geologic Carbon Dioxide Storage (Brennan et al., 2010)

(5) Lifetime of Carbon Capture and Storage as A Climate-Change Mitigation Technology (Szulczewski et al., 2012)

(6) A Method for Quick Assessment of CO_2 Storage Capacity in Closed and Semi-closed Saline Formations (Zhou et al., 2008)

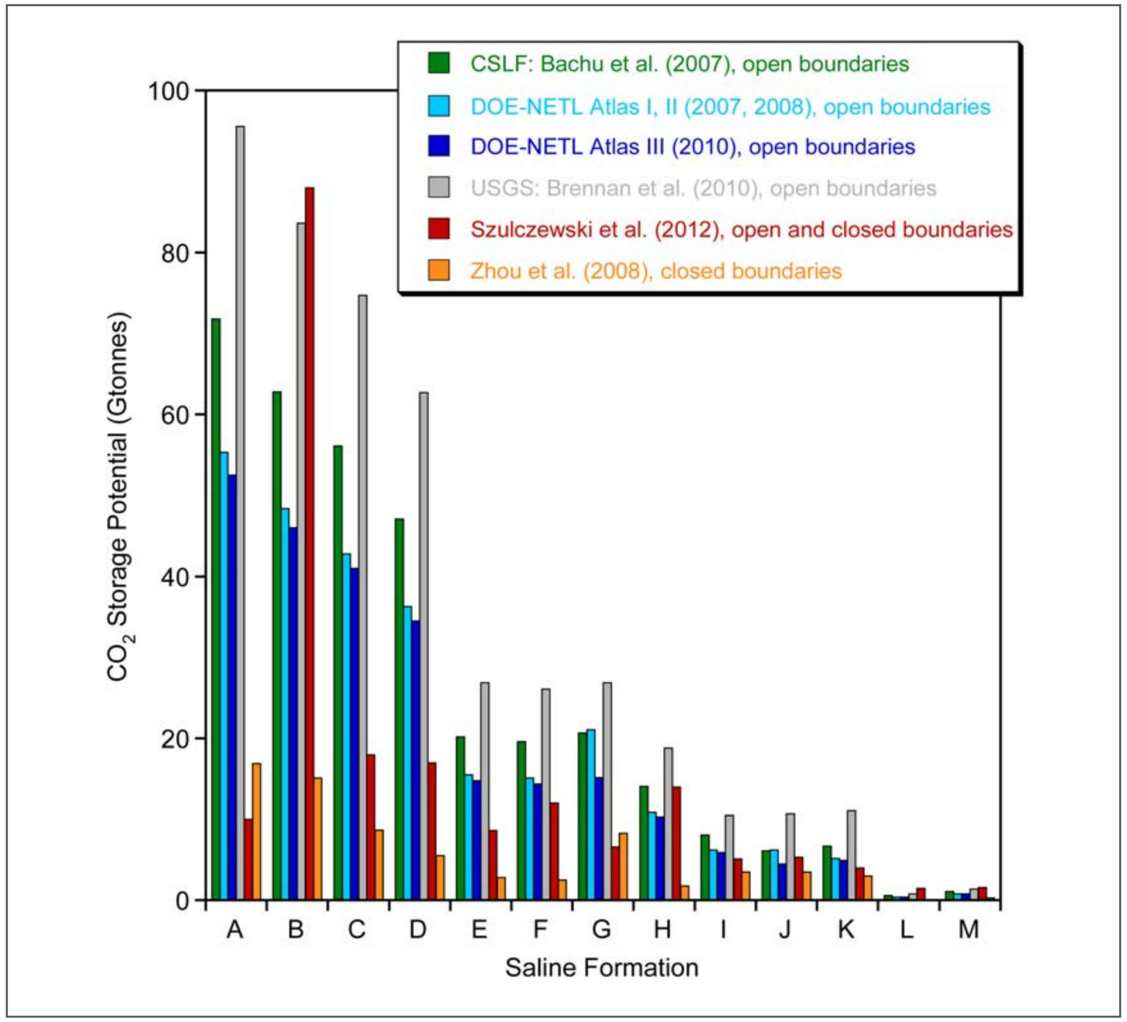
Methodologies selected for comparison assessed physical trapping of CO_2, where the estimates represent the fraction of pore volume in a formation of interest that will be occupied by CO_2 injected through drilled and completed wellbores. Trapping mechanisms considered were structural, hydrodynamic, residual, and solubility. Economic and regulatory considerations were not included. All methodologies assumed the following basic criteria:

(1) Pressure and temperature conditions in the saline formation are adequate to keep the CO_2 liquid or supercritical.

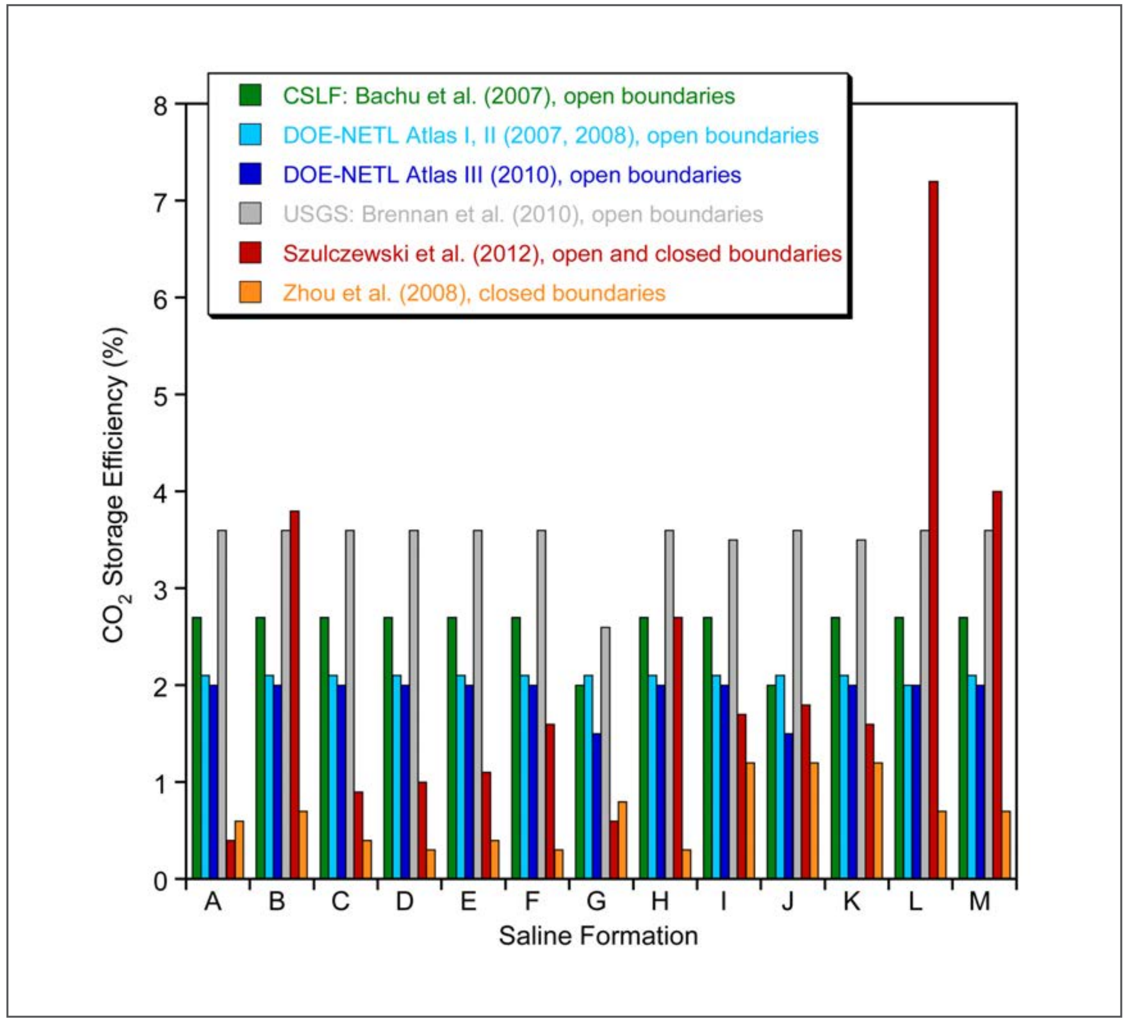
(2) A suitable seal system, such as a caprock, is present to limit vertical flow of the CO_2 to the surface.

(3) A combination of hydrogeologic conditions isolates the CO_2 within the saline formation.

The boundary conditions for the saline formation subsurface comparison were either considered to be open or closed. Open systems are permeable fluid-filled reservoirs where *in-situ* fluids will either be displaced away from the injection location into other parts of the formation and/or into neighboring formations or managed by means of fluid production, treatment, and disposal in accordance with current technical, regulatory, and economic guidelines. Closed systems are fluid-filled reservoirs where *in-situ* fluid movement is restricted within the formation by means of impermeable barriers.



CO_2 storage estimates at the 50th percent probability range for open and closed systems by the following methodologies: CSLF: Bachu et al. (2007), DOE-NETL Atlas I, II (2007, 2008), DOE-NETL Atlas III (2010), USGS: Brennan et al. (2010), Szulczewski et al. (2012), and Zhou et al. (2008).



Overall efficiency for CO_2 storage estimates at the 50th percent probability range for open and closed systems by the following methodologies: CSLF: Bachu et al. (2007), DOE-NETL Atlas I, II (2007, 2008), DOE-NETL Atlas III (2010), USGS: Brennan et al. (2010), Szulczewski et al. (2012), and Zhou et al. (2008).

Results

Several general trends were determined for the CO_2 storage estimates at the 50^{th} percent probability range for open and closed systems by the methodologies [CSLF: Bachu et al. (2007), DOE-NETL Atlas I, II (2007, 2008), DOE-NETL Atlas III (2010), USGS: Brennan et al. (2010), Szulczewski et al. (2012), and Zhou et al. (2008)]:

(1) The method by Zhou et al. (2008), typically, reports the lowest estimates.

(2) The method by USGS: Brennan et al. (2010), typically, reports the highest estimates.

For the open-boundary methodologies, in almost all cases the methodologies do not differ in a statistically significant way in each of the saline formation cases that were studied.

Although there are definite differences in the underlying assumptions for open- and closed-boundary methodologies, for most of the saline formation cases that were studied the variability in underlying parameters was still so great that the estimates of CO_2 storage resource from the closed-boundary method could not be statistically distinguished from those generated by the open-boundary methodologies. However, in some cases the open-boundary methodologies do give statistically significantly different results when compared to the closed-boundary methodology.

In general, the uncertainty in the underlying parameters has a much greater impact on overall estimates of CO_2 storage resource than the choice of methodology does, especially within subsets of methods defined by their boundary assumptions.

Conclusion

Several different resource estimation methodologies were applied to a wide range of different site types. As is currently typical for these types of estimates for carbon storage in saline fields, the data sets were very sparse. Most of the open system methodologies gave median results that were well within the uncertainty bounds of the others, suggesting that the uncertainty accounted for within each methodology is higher than the variability between the methodologies. Thus, the uncertainty in the underlying parameters has a much greater impact on overall estimates of CO_2 storage resource than uncertainty in the choice of methodology. Assessments of CO_2 storage potential made with different methods currently can be treated as giving comparable results relative to our typical knowledge of the relevant input values when assessing CO_2 storage potential at a high level.

The closed system estimates were consistently lower than those of the open system methodologies, but the estimated values from the closed system were also mostly well within the uncertainty bounds of the open system estimates. The fact that the closed methods often give lower results than the open methods suggests that statistically significant differences will ultimately be found in many cases, but maybe not in all cases, as uncertainty in the underlying parameters decreases.

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Appendix D: CO_2 Stationary Source and Geologic Storage Resource Estimates by State/Province

CO_2 Stationary Source Emission Estimates

The table ("Identified Stationary CO_2 Sources") displays CO_2 stationary source data by state/province which were obtained from the RCSPs and compiled by NATCARB. A total of more than 4,245 stationary sources with total annual emissions exceeding 3,279 million metric tons (3,614 million tons) of CO_2 have been documented by the RCSPs.

The states/provinces with the largest CO_2 stationary source emissions include Texas, Indiana, Pennsylvania, Ohio, Florida, Illinois, California, Louisiana, Alberta, and Kentucky. The 424 stationary sources identified in Texas are estimated to emit 371 million metric tons per year (409 million tons per year) of CO_2. The 96 stationary sources identified in Indiana are estimated to emit 156 million metric tons per year (172 million tons per year). The 100 stationary sources identified in Pennsylvania are estimated to emit 147 million metric tons per year (162 million tons per year).

Information on the methods used in estimating CO_2 stationary source emissions can be found in the "CO_2 Stationary Source Emission Estimation Methodologies Summary" in Appendix A. Emissions data specific to each RCSP can be found within each RCSP section of *Atlas IV*. Please refer all NATCARB map and data requests to natcarb.maps@netl.doe.gov.

Identified Stationary CO_2 Sources

State/Province	CO_2 Emissions Million Metric Ton Per Year	Number of Sources
Alabama	98	92
Alaska	14	42
Alberta	117	256
Arizona	60	54
Arkansas	38	39
British Columbia	12	67
California	129	284
Colorado	49	116
Connecticut	9	33
Delaware	5	16
District of Columbia	1	7
Florida	138	95
Georgia	90	73
Hawaii	11	18
Idaho	6	40
Illinois	134	188
Indiana	156	96
Iowa	61	75
Kansas	46	88
Kentucky	106	80
Louisiana	129	149
Maine	5	19
Manitoba	2	6
Maryland	33	23
Massachusetts	20	55
Michigan	93	62
Minnesota	53	107
Mississippi	38	48
Missouri	86	126
Montana	24	52
Nebraska	35	39
Nevada	20	25
New Brunswick	0	
New Hampshire	6	11
New Jersey	24	26
New Mexico	35	70
New York	47	67
Newfoundland & Labrador	0	
North Carolina	77	63
North Dakota	37	33
Northwest Territories	0	
Nova Scotia	0	
Offshore Federal Only	6	7
Ohio	146	85
Oklahoma	67	112
Ontario	0	
Oregon	17	48
Pennsylvania	147	100
Puerto Rico	17	10
Quebec	0	
Rhode Island	3	10
Saskatchewan	22	25
South Carolina	49	47
South Dakota	14	33
Tennessee	54	47
Texas	371	424
Utah	40	50
Vermont	0	5
Virginia	43	62
Washington	33	74
West Virginia	77	27
Wisconsin	68	215
Wyoming	63	124
North America Total	3,279	4,245

Total CO_2 Storage Resource Estimates

The table ("Total CO_2 Storage Resource") displays the total CO_2 storage resource estimates by state/province which were obtained from the RCSPs and compiled by NATCARB. The total CO_2 storage resource is the sum of oil and gas reservoir, saline formation, and unmineable coal CO_2 storage resource estimates. The current total CO_2 storage resource identified by the RCSPs is approximately 2,380 to 20,353 billion metric tons (2,625 to 22,435 billion tons).

Information on the methods used in estimating CO_2 storage resource can be found in the "Methodology for Development of Geologic Storage Estimates for Carbon Dioxide" in Appendix B. Please note CO_2 geologic storage information in *Atlas IV* was developed to provide a high level overview of CO_2 geologic storage potential. Carbon dioxide resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation of the extent to which geologic CO_2 storage is feasible. This information is not intended as a substitute for site-specific characterization, assessment, and testing. Please refer all NATCARB map and data requests to natcarb.maps@netl.doe.gov.

Total CO_2 Storage Resource*

State/Province	Million Metric Tons		Million Tons	
	Low Estimate	High Estimate	Low Estimate	High Estimate
Alabama	122,490	694,380	135,020	765,420
Alaska	8,640	19,750	9,520	21,770
Alberta	41,840	131,230	46,120	144,650
Arizona	130	1,170	140	1,280
Arkansas	6,180	63,670	6,810	70,190
British Columbia	910	3,860	1,000	4,250
California	33,890	420,630	37,360	463,660
Colorado	37,610	357,190	41,450	393,740
Connecticut				
Delaware	40	40	40	40
District of Columbia				
Florida	102,740	555,010	113,250	611,790
Georgia	145,340	159,050	160,210	175,320
Hawaii				
Idaho	40	390	40	430
Illinois	10,020	116,820	11,050	128,770
Indiana	32,020	68,210	35,300	75,180
Iowa	10	50	10	50
Kansas	10,880	86,340	11,990	95,170
Kentucky	2,920	7,650	3,220	8,440
Louisiana	169,500	2,103,980	186,840	2,319,240
Maine				
Manitoba	1,720	3,520	1,890	3,880
Maryland	1,860	1,930	2,050	2,130
Massachusetts				
Michigan	19,050	47,210	21,000	52,040
Minnesota				
Mississippi	145,010	1,185,030	159,850	1,306,270
Missouri	10	170	20	180
Montana	84,580	912,720	93,230	1,006,100
Nebraska	23,770	113,240	26,200	124,820
Nevada				
New Brunswick				
New Hampshire				
New Jersey	0	0	0	0
New Mexico	42,760	359,090	47,130	395,830
New York	4,640	4,640	5,110	5,110
Newfoundland & Labrador				
North Carolina	1,340	18,390	1,480	20,270
North Dakota	67,090	147,480	73,950	162,570
Northwest Territories				
Nova Scotia				
Offshore Federal Only	489,840	6,440,090	539,960	7,098,980
Ohio	13,460	13,460	14,830	14,830
Oklahoma	56,950	244,550	62,770	269,570
Ontario				
Oregon	6,810	93,700	7,510	103,290
Pennsylvania	22,100	22,100	24,360	24,360
Puerto Rico				
Quebec				
Rhode Island				
Saskatchewan	38,690	121,910	42,640	134,380
South Carolina	30,100	34,180	33,180	37,680
South Dakota	8,760	24,030	9,660	26,490
Tennessee	430	3,860	470	4,260
Texas	443,800	4,329,930	489,210	4,772,930
Utah	25,470	240,910	28,080	265,560
Vermont				
Virginia	440	2,910	490	3,210
Washington	36,620	496,730	40,360	547,560
West Virginia	16,650	16,650	18,350	18,350
Wisconsin	0	0	0	0
Wyoming	72,690	684,850	80,130	754,920
North America Total	2,379,840	20,352,700	2,623,300	22,434,990

* States/Provinces with a "zero" value represent estimates of minimal CO_2 storage resource, while states/provinces with a blank represent areas that have not yet been assessed by the RCSPs.

CO_2 Storage Resource Estimates for Oil and Gas Reservoirs

The table ("CO_2 Storage Resource Estimates for Oil and Gas Reservoirs") displays oil and gas reservoir CO_2 storage resource estimates by state/province. As described on page 25, the RCSPs have documented the location of more than 225 billion metric tons (248 billion tons) of CO_2 storage potential in oil and gas reservoirs. In the table, states/provinces with a "zero" value represent estimates of minimal oil and gas reservoir CO_2 storage resource while states/provinces with a blank represent areas that have not yet been assessed by the RCSPs. Carbon dioxide storage resource data for oil and gas reservoirs specific to each RCSP can be found within each RCSP section of *Atlas IV*. Additional details can be obtained from the NATCARB website (http://www.netl.doe.gov/technologies/carbon_seq/natcarb/index.html).

Areas with the largest oil and gas reservoir storage potential identified include Texas, Oklahoma, U.S. Federal Offshore, Alberta, Louisiana. New Mexico, Saskatchewan, West Virginia, Pennsylvania, and North Dakota. Carbon dioxide storage resource in Texas oil and gas reservoirs is significant, with an estimated 260 years of storage available at current emission rates. Oklahoma's oil and gas reservoirs are estimated to have CO_2 storage resource for more than 550 years of emissions from the state.

Please note CO_2 geologic storage information in *Atlas IV* was developed to provide a high level overview of CO_2 geologic storage potential. Carbon dioxide resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation of the extent to which geologic CO_2 storage is feasible. This information is not intended as a substitute for site-specific characterization, assessment, and testing. Please refer all NATCARB map and data requests to natcarb.maps@netl.doe.gov.

CO_2 Storage Resource Estimates for Oil & Gas Reservoirs*

State/Province	Million Metric Tons	Million Tons
Alabama	350	380
Alaska		
Alberta	10,080	11,110
Arizona	20	20
Arkansas	220	240
British Columbia		
California	3,560	3,920
Colorado	3,760	4,140
Florida	110	120
Illinois	110	120
Indiana	20	20
Kansas	1,250	1,380
Kentucky	70	80
Louisiana	9,830	10,840
Manitoba	860	950
Maryland	0	0
Michigan	470	520
Mississippi	550	610
Montana	2,440	2,690
Nebraska	30	30

State/Province	Million Metric Tons	Million Tons
Nevada		
New Mexico	9,710	10,700
New York	270	300
North Dakota	4,110	4,530
Northwest Territories		
Offshore Federal Only	17,140	18,890
Ohio	3,400	3,750
Oklahoma	37,310	41,130
Ontario		
Oregon		
Pennsylvania	4,490	4,950
Saskatchewan	6,970	7,680
South Dakota	170	190
Tennessee	10	10
Texas	98,160	108,210
Utah	2,980	3,280
Virginia	10	10
Washington		
West Virginia	5,090	5,610
Wyoming	1,700	1,870
North America Total	225,250	248,280

* States/Provinces with a "zero" value represent estimates of minimal CO_2 storage resource, while states/provinces with a blank represent areas that have not yet been assessed by the RCSPs.

CO_2 Storage Resource Estimates for Unmineable Coal

The table ("CO_2 Storage Resource Estimates for Unmineable Coal") displays unmineable coal CO_2 storage resource estimates by state/province. As described on page 26, the RCSPs have documented the location of more than 54 to 113 billion metric tons (59 to 124 billion tons) of CO_2 geologic storage potential in unmineable coal. In the table, states/provinces with a zero represent estimates of minimal unmineable coal CO_2 storage resource while states/provinces with a blank represent areas that have not yet been assessed by the RCSPs. Unmineable coal CO_2 storage resource data specific to each RCSP can be found within each RCSP section of *Atlas IV*. Additional details can be obtained from the NATCARB website (http://www.netl.doe.gov/technologies/carbon_seq/natcarb/index.html).

Areas with the largest unmineable coal CO_2 storage resource identified include Texas, Alaska, Louisiana, Mississippi, Wyoming, Alabama, Arkansas, Illinois, Florida, and Washington. An estimated 35 to 80 years of CO_2 storage resource is available in Texas unmineable coal for Texas's current emission rate. Alaska's unmineable coal is estimated to have CO_2 storage resource for an estimated 610 to 1,420 years worth of emissions.

Please note CO_2 geologic storage information in *Atlas IV* was developed to provide a high level overview of CO_2 geologic storage potential. Carbon dioxide resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation of the extent to which geologic CO_2 storage is feasible. This information is not intended as a substitute for site-specific characterization, assessment, and testing. Please refer all NATCARB map and data requests to natcarb.maps@netl.doe.gov.

CO_2 Storage Resource Estimates for Unmineable Coal*

State/Province	Million Metric Tons		Million Tons	
	Low Estimate	High Estimate	Low Estimate	High Estimate
Alabama	1,920	4,370	2,120	4,810
Alaska	8,640	19,750	9,520	21,770
Alberta	30	30	30	30
Arizona	0	0	0	0
Arkansas	1,580	3,610	1,740	3,980
British Columbia	0	0	0	0
California				
Colorado	490	860	540	940
Florida	1,260	2,850	1,390	3,140
Georgia	10	30	10	30
Idaho				
Illinois	1,450	2,870	1,600	3,160
Indiana	90	170	100	190
Iowa	0	10	0	10
Kansas	0	10	0	10
Kentucky	140	200	150	220
Louisiana	8,300	18,910	9,150	20,850
Maryland	0	0	0	0
Michigan	0	0	0	0
Mississippi	5,440	12,450	5,990	13,720
Missouri	0	10	0	10
Montana	330	330	370	370
Nebraska	0	0	0	0
Nevada				
New Mexico	80	300	80	330
New York				
North Dakota	540	540	600	600
Offshore Federal Only	1,690	3,860	1,860	4,250
Ohio	120	120	140	140
Oklahoma	0	10	0	10
Ontario				
Oregon				
Texas	14,020	32,030	15,450	35,300
Utah	30	120	30	140
Virginia	160	690	180	760
Washington	590	1,350	650	1,490
West Virginia	370	370	410	410
Wyoming	6,550	6,780	7,220	7,480
North America Total	54,100	112,900	59,630	124,450

* States/Provinces with a "zero" value represent estimates of minimal CO_2 storage resource, while states/provinces with a blank represent areas that have not yet been assessed by the RCSPs.

CO_2 *Storage Resource Estimates for Saline Formations*

The table ("CO_2 Storage Resource Estimates for Saline Formations") displays saline formation CO_2 storage resource estimates by state/province. As described on page 27, the RCSPs have documented the location of saline formations with an estimated storage potential from approximately 2,100 to more than 20,014 billion metric tons (from 2,315 to more than 22,062 billion tons). In the table, states/provinces with a zero represent estimates of saline formation CO_2 storage resource while states/provinces with a blank represent areas that have not yet been assessed by the RCSPs. Saline formation CO_2 storage resource data specific to each RCSP can be found within each RCSP section of *Atlas IV*. Additional details can be obtained from the NATCARB website (http://www.netl.doe.gov/technologies/carbon_seq/natcarb/index.html).

Areas with the largest saline formation CO_2 storage resource identified include U.S. Federal Offshore, Texas, Louisiana, Alabama, Mississippi, Montana, Wyoming, Florida, Washington, and California. At Texas's current emission rate, there is an estimated 880 to 11,200 years of CO_2 storage resource available in Texas saline formations. At Louisiana's current emission rate, there is an estimated 1,000 to 16,000 years of CO_2 storage resource available in Louisiana saline formations.

Please note CO_2 geologic storage information in *Atlas IV* was developed to provide a high level overview of CO_2 geologic storage potential. Carbon dioxide resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation of the extent to which geologic CO_2 storage is feasible. This information is not intended as a substitute for site-specific characterization, assessment, and testing. Please refer all NATCARB map and data requests to natcarb.maps@netl.doe.gov.

CO_2 Storage Resource Estimates for Saline Formations*

State/ Province	Million Metric Tons		Million Tons	
	Low Estimate	High Estimate	Low Estimate	High Estimate
Alabama	120,220	689,670	132,520	760,230
Alaska				
Alberta	31,730	121,120	34,980	133,510
Arizona	110	1,140	120	1,260
Arkansas	4,380	59,840	4,830	65,960
British Columbia	910	3,860	1,000	4,250
California	30,330	417,070	33,430	459,740
Colorado	33,360	352,580	36,770	388,650
Connecticut				
Delaware	40	40	40	40
District of Columbia				
Florida	101,370	552,050	111,740	608,530
Georgia	145,330	159,020	160,200	175,290
Hawaii				
Idaho	40	390	40	430
Illinois	8,460	113,850	9,330	125,490
Indiana	31,920	68,020	35,180	74,980
Iowa	0	40	0	40
Kansas	9,630	85,080	10,610	93,790
Kentucky	2,710	7,380	2,990	8,140
Louisiana	151,360	2,075,230	166,850	2,287,550
Manitoba	860	2,660	950	2,930
Maryland	1,860	1,930	2,050	2,130
Massachusetts				
Michigan	18,580	46,750	20,480	51,530
Mississippi	139,020	1,172,030	153,240	1,291,940
Missouri	10	150	10	170
Montana	81,810	909,950	90,180	1,003,050

State/ Province	Million Metric Tons		Million Tons	
	Low Estimate	High Estimate	Low Estimate	High Estimate
Nebraska	23,740	113,210	26,170	124,790
Nevada				
New Jersey	0	0	0	0
New Mexico	32,970	349,080	36,340	384,790
New York	4,370	4,370	4,810	4,810
North Carolina	1,340	18,390	1,480	20,270
North Dakota	62,440	142,830	68,830	157,440
Offshore Federal Only	471,010	6,419,090	519,200	7,075,830
Ohio	9,930	9,930	10,940	10,940
Oklahoma	19,640	207,240	21,640	228,440
Ontario				
Oregon	6,810	93,700	7,510	103,290
Pennsylvania	17,340	17,340	19,120	19,120
Quebec				
Rhode Island				
Saskatchewan	31,720	114,940	34,970	126,700
South Carolina	30,100	34,180	33,180	37,680
South Dakota	8,590	23,860	9,470	26,300
Tennessee	410	3,850	460	4,240
Texas	331,620	4,199,740	365,550	4,629,420
Utah	22,460	237,810	24,760	262,140
Vermont				
Virginia	270	2,210	300	2,440
Washington	36,030	495,390	39,710	546,070
West Virginia	11,190	11,190	12,340	12,340
Wisconsin	0	0	0	0
Wyoming	64,440	676,370	71,040	745,570
North America Total	2,100,460	20,014,570	2,315,360	22,062,250

* States/Provinces with a "zero" value represent estimates of minimal CO_2 storage resource, while states/provinces with a blank represent areas that have not yet been assessed by the RCSPs.

CO_2 Stationary Source Emissions and CO_2 Storage Resource Estimates Summary

This table ("CO_2 Emissions and Geologic Storage Resource Summary") is a compilation of all data provided in Appendix D. The states/provinces with a "zero" represent estimates of minimal CO_2 storage resource, while states/provinces with a blank represent areas that have not yet been accessed by the RCSPs.

Please note CO_2 geologic storage information in *Atlas IV* was developed to provide a high level overview of CO_2 geologic storage potential. Carbon dioxide resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation of the extent to which geologic CO_2 storage is feasible. This information is not intended as a substitute for site-specific characterization, assessment, and testing. Please refer all NATCARB map and data requests to natcarb.maps@netl.doe.gov.

CO_2 Stationary Source Emissions and CO_2 Storage Resource Estimates Summary*

CO_2 Emissions			Oil and Gas Reservoir Storage Resource	Unmineable Coal Storage Resource		Saline Formation Storage Resource		Total Storage Resource	
State/ Province	Million Metric Tons Per Year	No. Sources	Million Metric Tons	Million Metric Tons		Million Metric Tons		Million Metric Tons	
				Low Estimate	High Estimate	Low Estimate	High Estimate	Low Estimate	High Estimate
Alabama	98	92	350	1,920	4,370	120,220	689,670	122,490	694,380
Alaska	14	42		8,640	19,750			8,640	19,750
Alberta	117	256	10,080	30	30	31,730	121,120	41,840	131,230
Arizona	60	54	20	0	0	110	1,140	130	1,170
Arkansas	38	39	220	1,580	3,610	4,380	59,840	6,180	63,670
British Columbia	12	67		0	0	910	3,860	910	3,860
California	129	284	3,560			30,330	417,070	33,890	420,630
Colorado	49	116	3,760	490	860	33,360	352,580	37,610	357,190
Connecticut	9	33							
Delaware	5	16				40	40	40	40
District of Columbia	1	7							
Florida	138	95	110	1,260	2,850	101,370	552,050	102,740	555,010
Georgia	90	73		10	30	145,330	159,020	145,340	159,050
Hawaii	11	18							
Idaho	6	40				40	390	40	390
Illinois	134	188	110	1,450	2,870	8,460	113,850	10,020	116,820
Indiana	156	96	20	90	170	31,920	68,020	32,020	68,210
Iowa	61	75		0	10	0	40	10	50
Kansas	46	88	1,250	0	10	9,630	85,080	10,880	86,340
Kentucky	106	80	70	140	200	2,710	7,380	2,920	7,650
Louisiana	129	149	9,830	8,300	18,910	151,360	2,075,230	169,500	2,103,980
Maine	5	19							
Manitoba	2	6	860			860	2,660	1,720	3,520
Maryland	33	23	0	0	0	1,860	1,930	1,860	1,930
Massachusetts	20	55							
Michigan	93	62	470	0	0	18,580	46,750	19,050	47,210
Minnesota	53	107							
Mississippi	38	48	550	5,440	12,450	139,020	1,172,030	145,010	1,185,030
Missouri	86	126		0	10	10	150	10	170
Montana	24	52	2,440	330	330	81,810	909,950	84,580	912,720
Nebraska	35	39	30	0	0	23,740	113,210	23,770	113,240

* States/Provinces with a "zero" value represent estimates of minimal CO_2 storage resource, while states/provinces with a blank represent areas that have not yet been assessed by the RCSPs.

CO_2 Emissions			Oil and Gas Reservoir Storage Resource	Unmineable Coal Storage Resource		Saline Formation Storage Resource		Total Storage Resource	
State/ Province	Million Metric Tons Per Year	No. Sources	Million Metric Tons	Million Metric Tons		Million Metric Tons		Million Metric Tons	
				Low Estimate	High Estimate	Low Estimate	High Estimate	Low Estimate	High Estimate
Nevada	20	25							
New Brunswick	0								
New Hampshire	6	11							
New Jersey	24	26				0	0	0	0
New Mexico	35	70	9,710	80	300	32,970	349,080	42,760	359,090
New York	47	67	270			4,370	4,370	4,640	4,640
Newfoundland & Labrador	0								
North Carolina	77	63				1,340	18,390	1,340	18,390
North Dakota	37	33	4,110	540	540	62,440	142,830	67,090	147,480
Northwest Territories	0								
Nova Scotia	0								
Offshore Federal Only	6	7	17,140	1,690	3,860	471,010	6,419,090	489,840	6,440,090
Ohio	146	85	3,400	120	120	9,930	9,930	13,460	13,460
Oklahoma	67	112	37,310	0	10	19,640	207,240	56,950	244,550
Ontario	0								
Oregon	17	48				6,810	93,700	6,810	93,700
Pennsylvania	147	100	4,490	270	270	17,340	17,340	22,100	22,100
Puerto Rico	17	10							
Quebec	0								
Rhode Island	3	10							
Saskatchewan	22	25	6,970			31,720	114,940	38,690	121,910
South Carolina	49	47				30,100	34,180	30,100	34,180
South Dakota	14	33	170			8,590	23,860	8,760	24,030
Tennessee	54	47	10	0	0	410	3,850	430	3,860
Texas	371	424	98,160	14,020	32,030	331,620	4,199,740	443,800	4,329,930
Utah	40	50	2,980	30	120	22,460	237,810	25,470	240,910
Vermont	0	5							
Virginia	43	62	10	160	690	270	2,210	440	2,910
Washington	33	74		590	1,350	36,030	495,390	36,620	496,730
West Virginia	77	27	5,090	370	370	11,190	11,190	16,650	16,650
Wisconsin	68	215				0	0	0	0
Wyoming	63	124	1,700	6,550	6,780	64,440	676,370	72,690	684,850
North America Total	3,279	4,245	225,250	54,100	112,900	2,100,460	20,014,570	2,379,840	20,352,700

List of Acronyms and Abbreviations

2-D	Two-Dimensional
3-D	Three-Dimensional
ADM	Archer Daniels Midland
AoR	Area of Review
ARI	Advanced Resource International
ARRA	American Recovery and Reinvestment Act of 2009
Atlas IV	2012 United States Carbon Utilization and Storage Atlas
BLM	Bureau of Land Management
BOEM	Bureau of Ocean Energy Management
BSCSP	Big Sky Carbon Sequestration Partnership
BPM	Best Practice Manual
CBM	Coalbed Methane
CCPI	Clean Coal Power Initiative
CCRP	Clean Coal Research Program
CCS	Carbon Capture and Storage
CCSI	Carbon Capture and Storage Initiative
CCUS	Carbon Capture, Utilization, and Storage
CERC	U.S.-China Clean Energy Research Center
CO_2	Carbon Dioxide
COE	Cost of Electricity
CSLF	Carbon Sequestration Leadership Forum
CT	Computed Tomography
CTS	FE/NETL Carbon Dioxide Transport and Storage (Model)
DOI	U.S. Department of Interior
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EDX	Energy Data Exchange
ER	Enhanced Recovery
EGR	Enhanced Gas Recovery
EHR	Enhanced Hydrocarbon Recovery
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
EPA	U.S. Environmental Protection Agency
FE	Office of Fossil Energy
FEPs	Features, Events, and Processes
FERC	Federal Energy Regulatory Commission
FY	Fiscal Year
GCCSI	Global Carbon Capture and Storage Institute
GES	Geological and Environmental Sciences
GHG	Greenhouse Gas
GIS	Geographic Information System
GS	Geologic Storage
GSRA	Geologic Storage Risk Assessment
GW	Gigawatts

HECA	Hydrogen Energy California
IBDP	Illinois Basin-Decatur Project
ICCS	Industrial Carbon Capture and Storage
IEA	International Energy Agency
IEAGHG	IEA's Greenhouse Gas Program
IGCC	Integrated Gas Combined Cycle
IOGCC	Interstate Oil and Gas Compact Commission
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LIP	large igneous provinces
LLNL	Lawrence Livermore National Laboratory
mg/l	milligrams per liter
MGSC	Midwest Geological Sequestration Consortium
MMt	Million Metric Tons
MRCSP	Midwest Regional Carbon Sequestration Partnership
MVA	Monitoring, Verification, and Accounting
NACAP	North American Carbon Atlas Partnership
NACSA	North American Carbon Storage Atlas
NARUC	National Association of Regulatory Utility Commissioners
NATCARB	National Carbon Sequestration Database and Geographic Information System
NEMS	National Energy Modeling System
NETL	National Energy Technology Laboratory
NGCC	Natural Gas Combined Cycle
NRAP	National Risk Assessment Partnership
NRCan	Natural Resources Canada
PCOR	Plains CO_2 Reduction Partnership
PNNL	Pacific Northwest National Laboratory
OPPA	Office of Program Planning and Analyses (NETL)
ORD	Office of Research and Development (NETL)
R&D	Research and Development
RD&D	Research, Development, and Demonstration
RCSP(s)	Regional Carbon Sequestration Partnership(s)
RUA	Regional University Alliance
SECARB	Southeast Regional Carbon Sequestration Partnership
SENER	Mexican Ministry of Energy
STB	Surface Transportation Board
SWP	Southwest Regional Partnership on Carbon Sequestration
Tcf	trillion cubic feet
TRL	Technology Readiness Level
UIC	Underground Injection Control
USDWs	Underground Sources of Drinking Water
WESTCARB	West Coast Regional Carbon Sequestration Partnership
WY-CUSP	Wyoming Carbon Underground Storage Project

Carbon Storage Program Reference Shelf

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 Core R&D and Infrastructure, Systems Analyses capabilities, a FAQ information portal, information about the RCSPs with links to their websites, and an extensive reference shelf. Links to numerous resources can be accessed via the Carbon 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

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Printed in the United States
on recycled paper

December 2012