U.S. Department of Energy • Office of Fossil Energy
National Energy Technology Laboratory

Carbon Sequestration Atlas of the United States and Canada

Second Edition

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Foreword

The Department of Energy's (DOE's) Office of Fossil Energy National Energy Technology Laboratory (NETL) is proud to release the second edition of the *Carbon Sequestration Atlas of the United States and Canada (Atlas II)*. Production of this Atlas is the result of cooperation and coordination among carbon sequestration experts from local, state, and federal agencies, as well as industry and academia. *Atlas II* provides a coordinated update of carbon capture and storage (CCS) potential across the majority of the U.S. and portions of Canada. The primary purpose of *Atlas II* is to update the carbon dioxide (CO_2) storage portfolio, document differences in CO_2 storage resource and CO_2 capacity, and provide updated information on the Regional Carbon Sequestration Partnerships (RCSPs) field activities. In addition, this Atlas provides an introduction to the carbon storage (sequestration) process and summarizes the DOE's Carbon Sequestration Program. It also presents updated information on the location of stationary CO_2 emission sources and the locations and storage potential of various geologic sequestration sites, and provides information about the commercialization opportunities for CCS technologies from each RCSP.

A key aspect of CCS is the amount of carbon storage potential available to effectively help address global climate change. As shown in this Atlas, CCS holds great promise as part of a portfolio of technologies that enables the U.S. and the rest of the world to effectively address climate change while meeting the energy demands of an ever increasing global population. This Atlas includes the most current and best available estimates of potential CO_2 storage resources determined by a methodology applied consistently across all of the RCSPs. A CO_2 **storage 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 storage resource assessments do not include economic or regulatory constraints; only physical and chemical constraints to define the accessible part of the subsurface are applied. Economic and regulatory constraints are included in geologic CO_2 capacity estimates. Under the most favorable economic and regulatory scenarios, 100 percent of the estimated CO_2 storage resource may be considered CO_2 capacity. The RCSPs have documented the location of more than 4,600 stationary sources with total annual emissions of over 3,200 million metric tons of CO_2. With a total estimated CO_2 storage resource over 3,500 billion metric tons in oil and gas reservoirs, coal seams, and saline formations, preliminary estimates suggest over 1,100 years of CO_2 storage in geologic formations in the U.S. and portions of Canada.

All data in *Atlas II* were collected before June 2008. It is acknowledged that these data sets are not comprehensive; it is, however, anticipated that CO_2 storage resource estimates as well as geologic formation maps will be updated every 2 years as new data are acquired and methodologies for CO_2 storage estimates improve. Further, it is expected that, through the ongoing work of the RCSPs, data quality and conceptual understanding of the CCS process will improve, resulting in more refined CO_2 storage estimates.

About this Atlas

The second edition of the *Carbon Sequestration Atlas of the United States and Canada* contains three main sections: (1) Introduction, (2) National Perspectives, and (3) Regional Perspectives. The Introduction section contains an overview of CCS technologies, a summary of the DOE's efforts in the CCS area, a brief description of the RCSP Program, and information on the National Carbon Sequestration Database and Geographic Information System (NATCARB). The National Perspectives section provides maps showing the number, location, and magnitude of identified CO_2 stationary sources in the U.S. and portions of Canada, as well as the areal extent and estimated CO_2 storage resource available in geologic formations evaluated within the RCSP Regions. The National Perspectives section also contains a summary of the methodologies and assumptions employed to calculate CO_2 emissions and estimated CO_2 storage resource of various geologic formations. The Regional Perspectives section includes a detailed presentation of CO_2 stationary sources, CO_2 storage resource assessments, updates on field projects, and information on commercialization opportunities in each RCSP based on these methodologies and assumptions.

The U.S. Department of Energy and the National Energy Technology Laboratory would like to acknowledge all who have contributed to this *Altas*.

Contents

4 Introduction

- The Greenhouse Gas Effect 4
- A Technology Approach to Reduce GHG Emissions 5
- What is Carbon Sequestration? 6
- DOE's Carbon Sequestration Program 7
- Regional Carbon Sequestration Partnerships 8
- Regional Carbon Sequestration Partnerships—Validation Phase CO_2 Storage Projects 9
- Regional Carbon Sequestration Partnerships—Development Phase 10
- Regional Carbon Sequestration Partnerships—Development Tests 11
- National Carbon Sequestration Database and Geographical Information System 12

14 National Perspectives

- Methodologies Used to Estimate CO_2 Stationary Source Emissions and CO_2 Geologic Storage Potential 14
- Carbon Dioxide Sources 17
- Oil and Gas Reservoirs 18
- Unmineable Coal Seams 19
- Deep Saline Formations 20
- Future Geologic Sequestration Options 21
- Terrestrial Sequestration 22
- United States Geological Survey 23
- Federal Land 24
- CO_2 Pipeline Studies at NETL 26

29 Regional Carbon Sequestration Partnership Perspectives

- Big Sky Carbon Sequestration Partnership 30
- Midwest Geological Sequestration Consortium 40
- Midwest Regional Carbon Sequestration Partnership 50
- The Plains CO_2 Reduction Partnership 60
- Southeast Regional Carbon Sequestration Partnership 70
- Southwest Regional Partnership on Carbon Sequestration 80
- West Coast Regional Carbon Sequestration Partnership 90

100 Appendix A: CO_2 Stationary Source Emission Estimation Methodologies Summary

115 Appendix B: Methodology for Development of Geologic Storage Estimates for Carbon Dioxide

133 Appendix C: Stationary Source and Geologic Storage Estimates for Carbon Dioxide by State/Province

Photo Credit—World image on front cover courtesy of NASA

The Greenhouse Gas Effect

Greenhouse gases (GHGs) are gas phase components of the atmosphere that contribute to the greenhouse gas effect, the trapping of radiant heat from the sun within the Earth's atmosphere. One GHG of particular interest is carbon dioxide (CO_2) because it is one of the most prevalent of all GHGs. Carbon dioxide is a colorless, odorless, nonflammable gas. Atmospheric CO_2 originates from both natural and man-made sources. There are multiple natural sources of CO_2, including volcanic outgassing, the combustion and decay of organic matter, and the respiration processes of organisms. Man-made, or anthropogenic, sources of CO_2 are primarily the burning of various fossil fuels for power generation and transportation, although other industrial activities contribute to atmospheric CO_2 concentrations as well.

The GHG effect is a natural and important phenomenon of the Earth's ecosystem. However, GHG levels in the atmosphere have significantly increased above the pre-industrial level according to the Energy Information Administration (EIA). Emissions of CO_2 from human activity have increased from an insignificant level two centuries ago to annual emissions of over 28 billion metric tons (31 billion tons) worldwide today. This increase in atmospheric GHGs is considered by many scientists to be a contributing factor to the phenomenon of global warming and a potential cause of unwelcome shifts in regional climates.

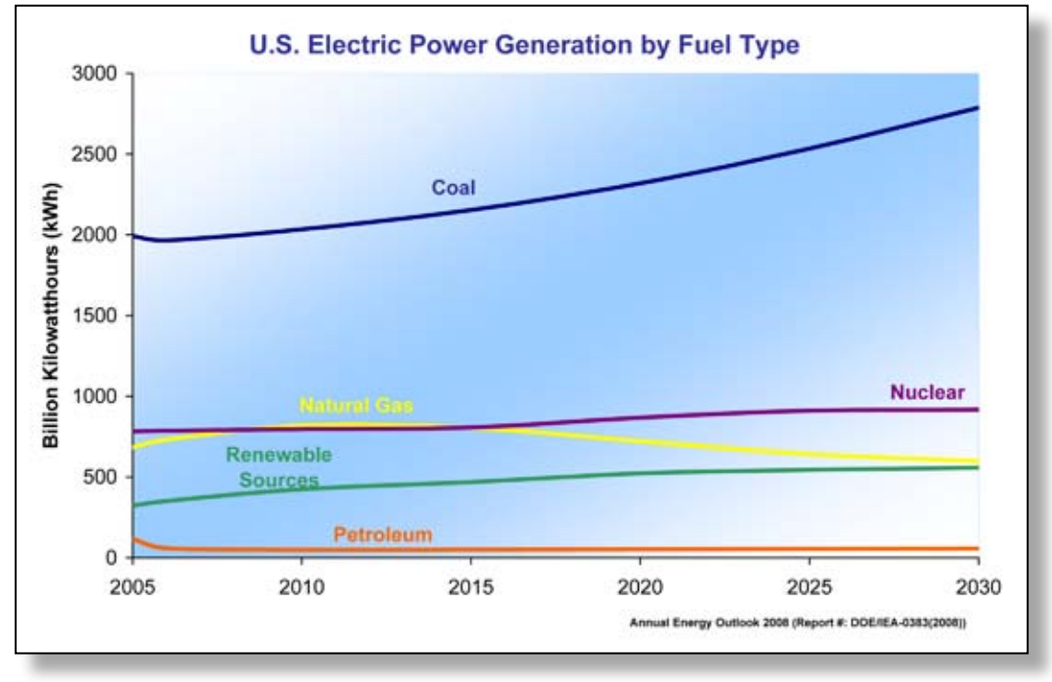
The U.S. is one of 192 countries that are signatories to the United Nations Framework Convention on Climate Change (UNFCC), a treaty approved in 1992 which calls for stabilization of atmospheric GHGs at a level that would prevent anthropogenic interference with the world's climate. Conservation, renewable energy, and improvements in the efficiency of power plants, automobiles, and other energy-consuming devices are important first steps in any GHG emissions mitigation effort. Those approaches, however, cannot deliver the level of emissions reduction needed to stabilize the concentrations of GHGs in the atmosphere—especially in view of a growing global demand for energy and the associated increase in GHG emissions. Technological approaches that are effective in reducing atmospheric GHG concentrations and, at the same time, have little or no negative impacts on energy use and economic growth and prosperity are needed. Carbon capture and storage (CCS) promises to provide a significant reduction in GHG emissions.

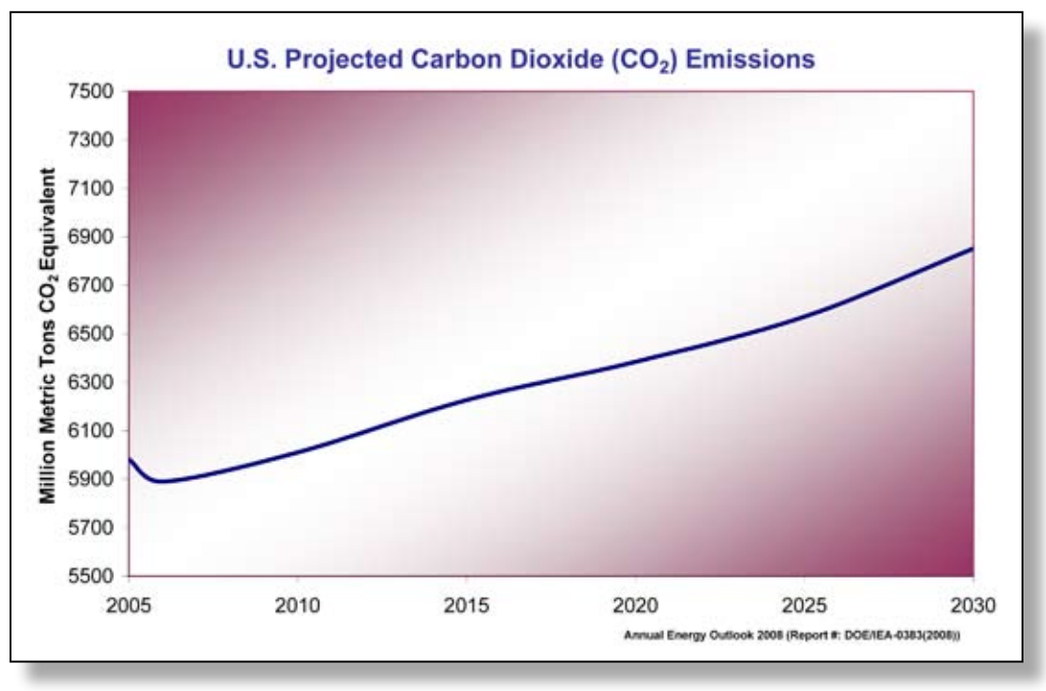
A Technology Approach to Reduce GHG Emissions

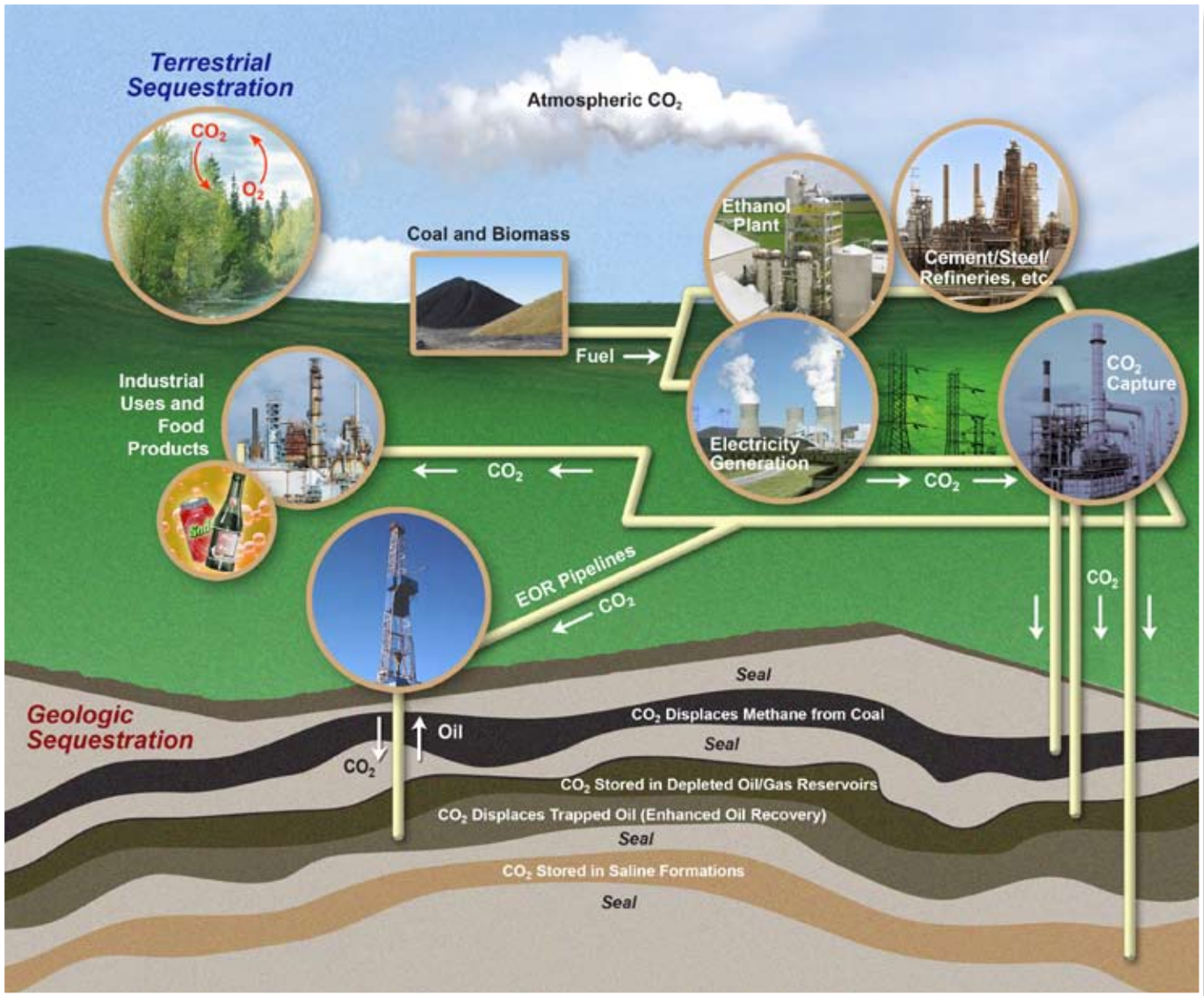
The U.S. Department of Energy's (DOE's) Office of Fossil Energy National Energy Technology Laboratory (NETL) is engaged in a research and development (R&D) Carbon Sequestration Program focusing on CCS technologies with significant potential for reducing GHG emissions and mitigating global climate change. The Program supports the UNFCC goal to reduce GHG emissions, as well as the National Energy Policy goals targeting the development of new technologies for reducing GHG emissions.

The graph "U.S. Electric Power Generation by Fuel Type," shown at top right, displays the *Annual Energy Outlook's* 2008 predictions of growth in energy generation by various fuel types. Coal is predicted to continue to dominate power generation for the next 25 years. Power generation from coal is one significant source of CO_2 emissions, making efforts to reduce these emissions a critical R&D goal.

The Energy Information Administration's graph titled "U.S. Projected Carbon Dioxide (CO_2) Emissions," shown at bottom right, illustrates the projected increase in CO_2 emissions over the next 25 years. Following AEO's 2008 assumptions, if no additional actions are taken, the U.S. will emit approximately 6,850 million metric tons (7,550 million tons) of CO_2 by 2030, increasing 2005 emission levels by more than 14 percent. The U.S. can work toward reducing GHG emissions with the development and implementation of appropriate CCS technologies.







What is Carbon Sequestration?

What is Carbon Sequestration?

Carbon sequestration encompasses the processes of capturing and storing CO_2 that would otherwise reside in the atmosphere for long periods of time. DOE is investigating a variety of carbon sequestration options. Geologic carbon sequestration involves the separation and capture of CO_2 at the point of emissions from stationary sources followed by storage in deep underground geologic formations. Terrestrial carbon sequestration involves the net removal of CO_2 from the atmosphere by plants during photosynthesis and its fixation in vegetative biomass and in soils.

It is expected that large numbers of new power plants and fuel processing facilities will be built in the coming decades, in both the developing world, as well as in some areas of the developed world, such as the U.S. and Canada. These new facilities, along with existing plants having the potential to be appropriately retrofitted, will create ample opportunities for deploying efficient and cost-effective CO_2 capture technologies. DOE's CO_2 capture efforts seek to cost-effectively capture and purify CO_2 using post-combustion, pre-combustion, or oxy-combustion technologies.

Geologic carbon sequestration is defined as the placement of CO_2 into a subsurface formation in such a way that it will remain permanently stored. DOE is investigating five types of underground formations for geologic carbon sequestration, each with different challenges and opportunities: (1) oil and natural gas reservoirs, (2) deep unmineable coal seams, (3) deep saline formations, (4) oil- and gas-rich organic shales, and (5) basalt formations.

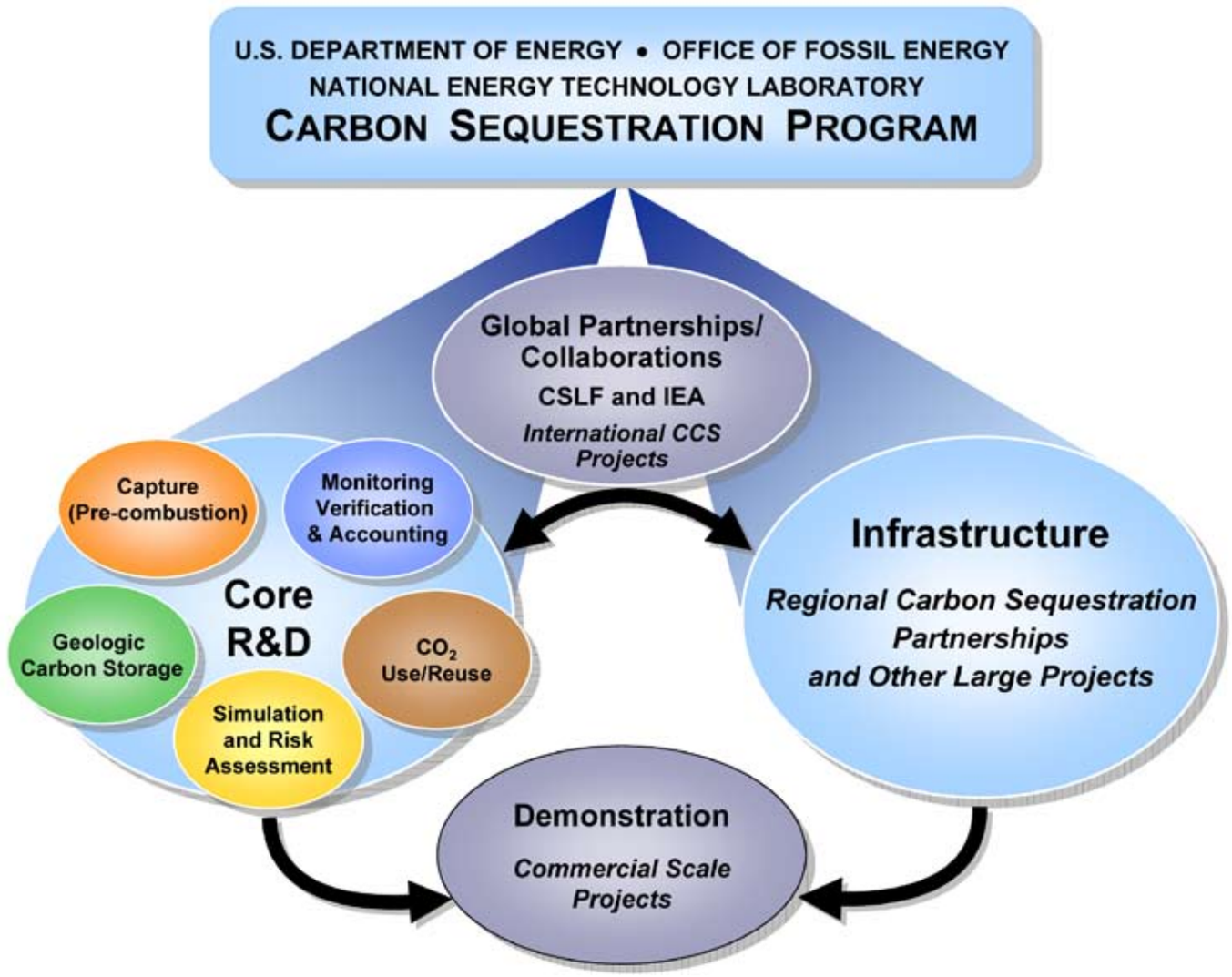
The process of carbon sequestration includes monitoring, verification, and accounting (MVA), as well as risk assessment, at the sequestration site. DOE's MVA efforts focus on development and deployment of technologies that can provide an accurate accounting of stored CO_2 and a high level of confidence that the CO_2 will remain permanently sequestered. Effective application of these MVA technologies will ensure the safety of sequestration projects with respect to the environment, and provide the basis for establishing carbon credit trading markets for sequestered CO_2. Risk assessment research focuses on identifying and quantifying potential risks to humans and the environment associated with carbon sequestration, and helping to ensure that these risks remain low.

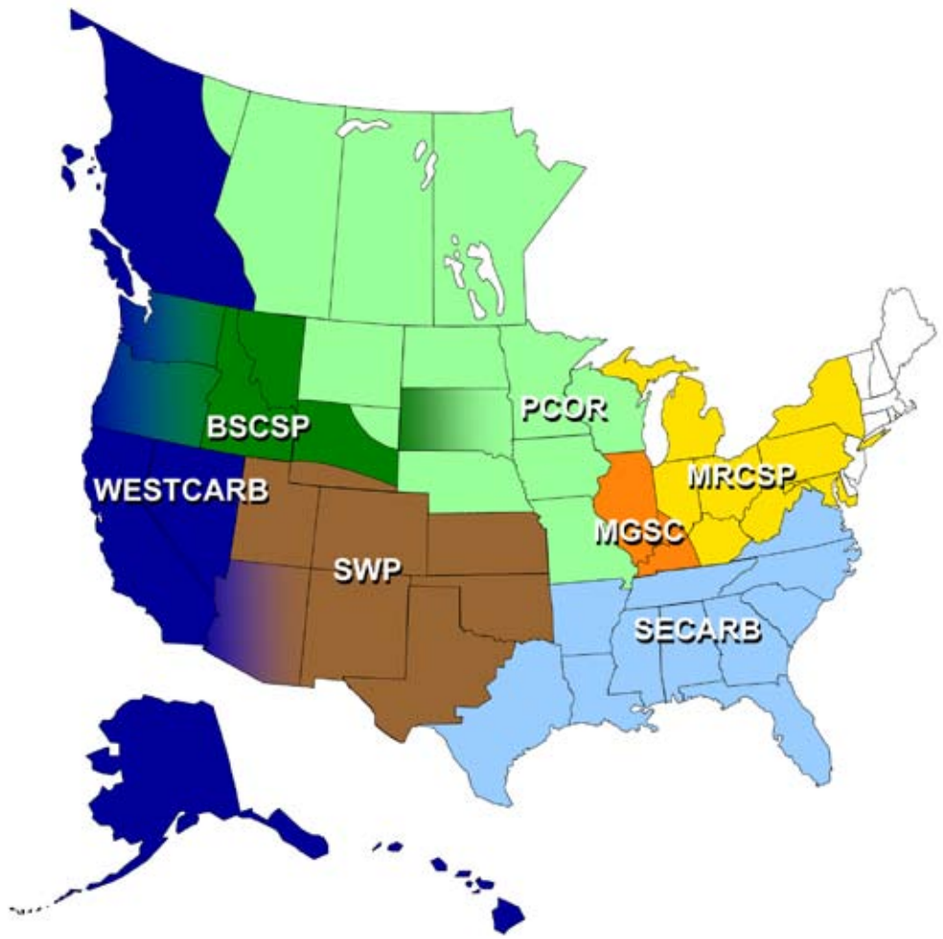
DOE's Carbon Sequestration Program

DOE's Carbon Sequestration Program involves two key elements for technology development and research: (1) Core R&D and (2) Infrastructure. The Core R&D element contains five focal areas for carbon sequestration technology development: (1) Pre-combustion Capture, (2) Geologic Carbon Storage, (3) Monitoring, Verification, and Accounting, (4) CO_2 Use/Reuse, and (5) Simulation and Risk Assessment. Core R&D is driven by technology needs and is accomplished through laboratory and pilot-scale research aimed at developing new technologies and new systems for GHG mitigation. The Infrastructure element includes large-scale projects and the Regional Carbon Sequestration Partnerships (RCSPs), a government/industry cooperative effort tasked with developing guidelines for the most suitable technologies, regulations, and infrastructure needs for CCS in different regions of the U.S. and Canada. The Core R&D and Infrastructure elements provide technology solutions which support the Global Partnerships/Collaborations and Demonstration elements.

DOE participates in international collaborations in the area of carbon sequestration, via the Carbon Sequestration Leadership Forum (CSLF). The CSLF is an international group that is focused on the development of improved, cost-effective technologies for the separation and capture of CO_2, transport of CO_2, and long-term safe storage of CO_2. The purpose of the CSLF is to make these technologies available internationally and to identify and address wider issues relating to carbon capture and storage, such as regulatory and policy options.

DOE's Carbon Sequestration Program is developing a portfolio of technologies with great potential to reduce GHG emissions. The Program's goal is to have a technology portfolio by 2012 for safe, cost-effective, and long-term carbon mitigation, management, and storage, which will lead to substantial market penetration after 2012. Reaching this goal requires an integrated R&D plan that will advance fundamental CCS technologies and prepare them for commercial-scale development. The Program works in concert with several programs within the Office of Fossil Energy that are developing and demonstrating technologies integral to coal-fueled power generation and coal conversion with potential for carbon capture, including Innovations for Existing Plants, Fuels, Clean Coal Power Initiative, Gasification, Fuel Cells, Turbines, and Advanced Research. Projects that meet the Program goal will result in large-scale units that come on-line around 2020. In the long-term, the Program is expected to contribute significantly to the reduction of GHG emissions.





Regional Carbon Sequestration Partnerships

Initiated by DOE's Office of Fossil Energy, the Regional Carbon Sequestration Partnerships (RCSPs) (see map at left) are a public/private cooperative effort tasked with developing guidelines for the most suitable technologies, regulations, and infrastructure needs for CCS in different regions of the U.S. and Canada. The energy sectors of both countries are very closely related. Geographical differences in fossil fuel use and CO_2 storage potential across the U.S. and Canada dictate regional approaches to sequestration of CO_2 and other GHGs. The seven RCSPs that form this network currently include more than 350 state agencies, universities, and private companies, spanning 42 states, and four Canadian provinces. In addition, agencies from six member countries of the CSLF are participating.

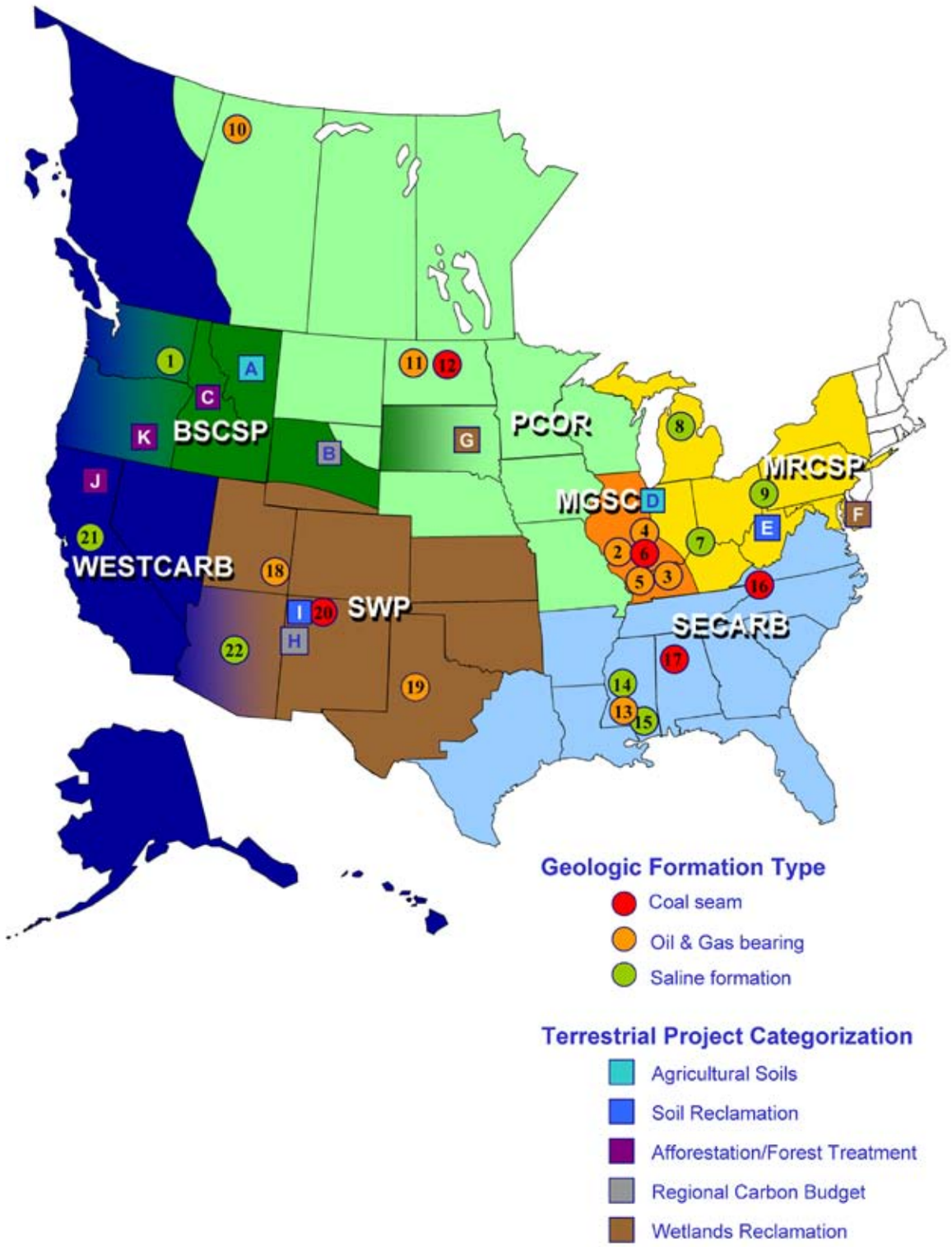
The RCSPs' effort consists of three distinct phases: (1) Characterization Phase (2003-2005); (2) Validation Phase (2005–2009); and (3) Development Phase (2008-2018). The Characterization Phase began in September 2003 with seven RCSPs working to develop the necessary framework to validate and potentially deploy CCS technologies. At the end of the Characterization Phase, the RCSPs had succeeded in establishing a national network of companies and professionals working to support CCS deployments, creating a National Carbon Sequestration Database and Geographic Information System (NATCARB), and raising awareness and support for CCS as a GHG mitigation option.

The Validation Phase focuses on validating the most promising regional opportunities to deploy CCS technologies by building upon the accomplishments of the Characterization Phase. Two different CO_2 storage approaches are being pursued in this phase: geologic and terrestrial carbon sequestration. Efforts are being conducted to (1) validate and refine current reservoir simulations for CO_2 storage projects; (2) collect physical data to confirm CO_2 storage potential and injectivity estimates; (3) demonstrate the effectiveness of MVA technologies; (4) develop guidelines for well completion, operations, and abandonment; and (5) develop strategies to optimize the CO_2 storage potential of various geologic formations.

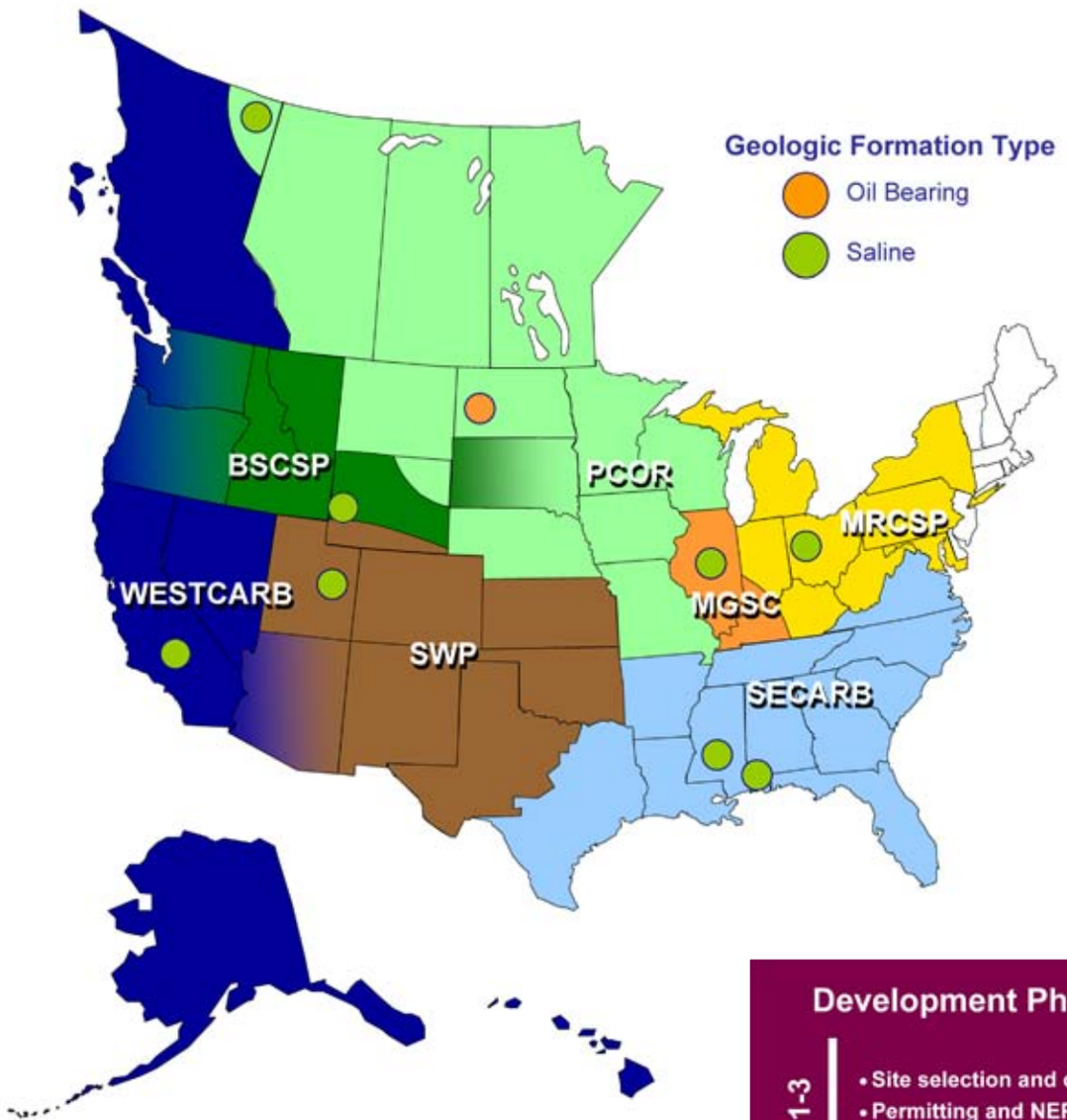
The Development Phase builds on the information generated in the Characterization and Validation Phases and involves the injection of 1 million tons or more of CO_2 by each RCSP into regionally significant geologic formations of different depositional environments. These large-volume injection tests 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. Results obtained from these efforts will provide the foundation for CCS technology commercialization throughout the United States.

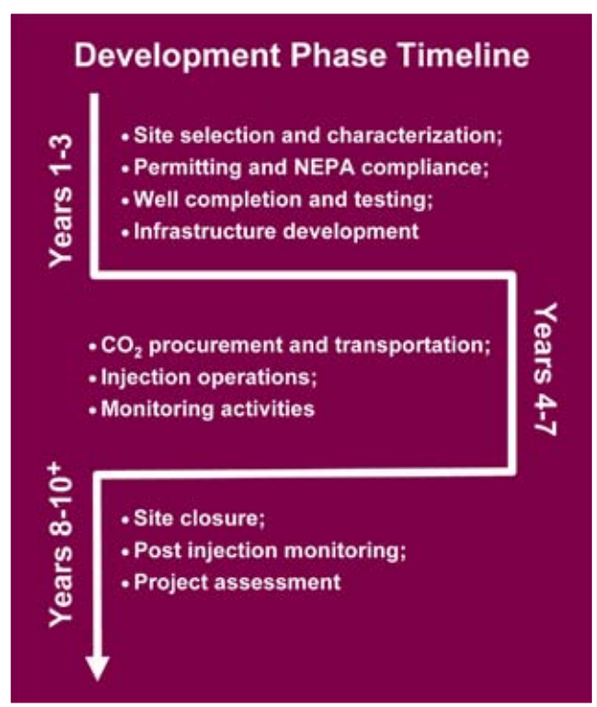
Regional Carbon Sequestration Partnership	Lead Organization	Member States/Provinces	Website
Big Sky Carbon Sequestration Partnership (BSCSP)	Montana State University	Montana, Idaho, South Dakota, Wyoming, Eastern Oregon and Washington, and adjacent areas in British Columbia and Alberta	http://www.bigskyco2.org/
Midwest Geological Sequestration Consortium (MGSC)	Illinois State Geological Survey	Illinois, Western Indiana, and Western Kentucky	http://www.sequestration.org/
Midwest Regional Carbon Sequestration Partnership (MRCSP)	Battelle Memorial Institute	Eastern Indiana, Eastern Kentucky, Maryland, Michigan, New York, Ohio, Pennsylvania, and West Virginia	http://www.mrcsp.org
Plains CO_2 Reduction (PCOR) Partnership	University of North Dakota, Energy and Environmental Research Center	Eastern Montana, Eastern Wyoming, Nebraska, Eastern South Dakota, North Dakota, Minnesota, Wisconsin, Iowa, Missouri, Alberta, Saskatchewan, Manitoba, and Northeastern British Columbia	http://www.undeerc.org/PCOR/
Southeast Regional Carbon Sequestration Partnership (SECARB)	Southern States Energy Board	East Texas, Arkansas, Louisiana, Mississippi, Alabama, Tennessee, Florida, Georgia, South Carolina, North Carolina, and Virginia	http://www.secarbon.org/
Southwest Regional Partnership (SWP)	New Mexico Institute of Mining and Technology	Western Texas, Oklahoma, Kansas, Colorado, Utah, and Eastern Arizona	http://www.southwestcarbonpartnership.org/
West Coast Regional Carbon Sequestration Partnership (WESTCARB)	California Energy Commission	Alaska, Western Arizona, Western British Columbia, California, Hawaii, Nevada, Western Oregon, and Western Washington	http://www.westcarb.org/

Regional Carbon Sequestration Partnerships—Validation Phase CO_2 Storage Projects



	Partnership	Geologic Province / Project Location	Geologic: Total CO_2 Injection (tons CO_2)	Geologic: Approximate Depth (feet)	Terrestrial: Estimated CO_2 Capacity
1		Columbia Basin	3,000	2,500 – 4,000	
A	Big Sky Carbon	North Central MT			60 Mt over 20 years
B		Eastern WY			30 Mt over 10 years
C		Region-wide			640 - 1,040 Mt over 80 yrs
2	MGSC	Illinois Basin	50	1,550	
3		Illinois Basin	1,000	1,549	
4		Illinois Basin	3,000	1,548	
5		Illinois Basin	3,000	1,551	
6		Illinois Basin	200	1,000	
7	MRCSP	Cincinnati Arch	3,000	3,200 – 3,500	
8		Michigan Basin	10,000	3,200 – 3,500	
9		Appalachian Basin	3,000	5,900 – 8,300	
D		Region-wide			25 Mt over 20 years
E		Region-wide			100 Mt over 20 years
F		Cambridge, MD			TBD
10	PCOR	Keg River Formation	100,000	5,000	
11		Duperow Formation	<1,000	10,000 – 10,500	
12		Williston Basin	<1,000	1,600 – 1,800	
G		Great Plains wetlands complex (PPR)			14.4 Mt
13	SECARB	Gulf Coast (stacked test)	500,000	10,304	
14		Gulf Coast (stacked test)		10,400	
15		Mississippi Coastal Plain	3,000	8,600	
16		Central Appalachian	1,000	1,600 – 2,300	
17		Black Warrior Basin	1,000	1,500 – 2,500	
18	SWP	Paradox Basin, Aneth Field	450,000	5,600 – 5,800	
19		Permian Basin	900,000	5,800	
20		San Juan Basin	75,000	3,000	
H		Region-wide			TBD
I		San Juan Basin Coal Fairway (Navajo City, NM)			TBD
21	WESTCARB	Sacramento Basin	2,000	8,000	
22		Colorado Plateau	2,000	4,000	
J		Shasta County, CA			4,600 Mt over 80 years (CA)
K		Lake County, OR			900 Mt over 80 years (OR)





Regional Carbon Sequestration Partnerships—Development Phase

The Development Phase, which began in FY 2008 and is planned to continue through FY 2018, will demonstrate at large scale that CO_2 capture, transportation, injection, and storage can be achieved safely, permanently, and economically. The geologic structures to be tested during these RCSP large-volume sequestration tests (see map at left) may become candidate sites for future near zero emissions power plants. The primary goal of the Development Phase is to establish large-scale CCS projects across North America, where large volumes of CO_2 will be injected into a geologic storage formation containing significant sequestration potential in each Region. Each project will inject CO_2 over several years. Recognizing that CO_2 sources vary widely from region to region and that some regions will have limited access to large volumes of CO_2, injection volumes may vary. The RCSPs, however, are expected to maximize CO_2 injection volumes and fully utilize the infrastructure of their Region. Projects that procure CO_2 from post-combustion capture facilities and industrial vents will inject at least 1 million tons, while projects receiving CO_2 from natural gas processing plants or natural vents will inject over a million tons of CO_2, depending upon cost and availability. The Development Phase tests will be implemented in three stages, which will test key technologies during the project's life-cycle (see graphic at left).

While projects in the Validation Phase are designed to demonstrate that regional sequestration sites have the potential to store thousands of years' worth of CO_2 emissions in the U.S., the large-volume sequestration tests in the Development Phase will also address practical issues such as sustainable injectivity, well design for both integrity and increased capacity, and reservoir behavior with respect to prolonged CO_2 injection. Development Phase goals include: (1) collect physical data to confirm capacity and injectivity estimates made during the Characterization Phase; (2) validate the effectiveness of simulation models to predict and MVA technologies to measure CO_2 movement in the geologic formations, confirm the integrity of the seals, and confirm indirect storage in terrestrial ecosystems; (3) develop guidelines for well completion, operations, and closure in order to maximize storage potential and mitigate leakage; (4) develop strategies for optimizing storage capacity for various reservoir types; (5) develop public outreach strategies and communicate the benefits of CCS to various stakeholders; and (6) satisfy the regulatory and permitting requirements for CCS projects.

Regional Carbon Sequestration Partnerships—Development Tests*

Big Sky Carbon Sequestration Partnership—With the cooperation of industry partners, Cimarex and Schlumberger, the BSCSP plans to inject up to 2.7 million metric tons (3 million tons) of CO_2 from a Cimarex Energy gas processing plant into the Nugget Sandstone on the Riley Ridge Unit on the LaBarge Platform in southwest Wyoming. The Nugget sandstone represents a key opportunity for sequestration in the region because it can potentially store more than 100 years of current emissions from power plants in Wyoming and is similar to other sequestration target saline aquifers in the region.

Midwest Geological Sequestration Consortium—MGSC is partnering with the Archer Daniels Midland (ADM) Company to conduct a deep > 1,500 m (> 5,000 ft) large-scale test into the ~460 m (~1,500 ft) thick Mt. Simon Sandstone in the Illinois Basin. One million metric tons of CO_2 (1.1 million tons) from ADM's ethanol production facility will be injected over three years at ADM's plant site. The lower porous Mt. Simon is understood to have been deposited in a braided stream and alluvial fan system within a pull-apart basin. The injection will test the effects of heterogeneity of the formation on capacity and containment.

Midwest Regional Carbon Sequestration Partnership—In the Development Phase, MRCSP will validate large-volume CO_2 storage in a relatively shallow 900 m (3,000 ft) and thin 90 m (300 ft) portion of the Mt. Simon sandstone formation by injecting one million tons of CO_2 over four years from an ethanol production facility. The Andersons Marathon Ethanol LLC (TAME) Plant will be the injection site for MRCSP's test and the source of CO_2 for this test.

Plains CO_2 Reduction Partnership—During the Development Phase, the PCOR Partnership's large-volume injection test in Canada's Alberta Basin will validate the co-sequestration of CO_2 and hydrogen sulfide from a large gas processing plant into a deep saline formation. In addition, PCOR Partnership will transport approximately one million metric tons of CO_2 per year for five years from the Antelope Valley Station, a coal-fired power plant in central North Dakota. The CO_2 will be injected into an oil reservoir located in western North Dakota. This large-scale test will validate both EOR and CO_2 storage in a deep carbonate formation that is also a saline formation.

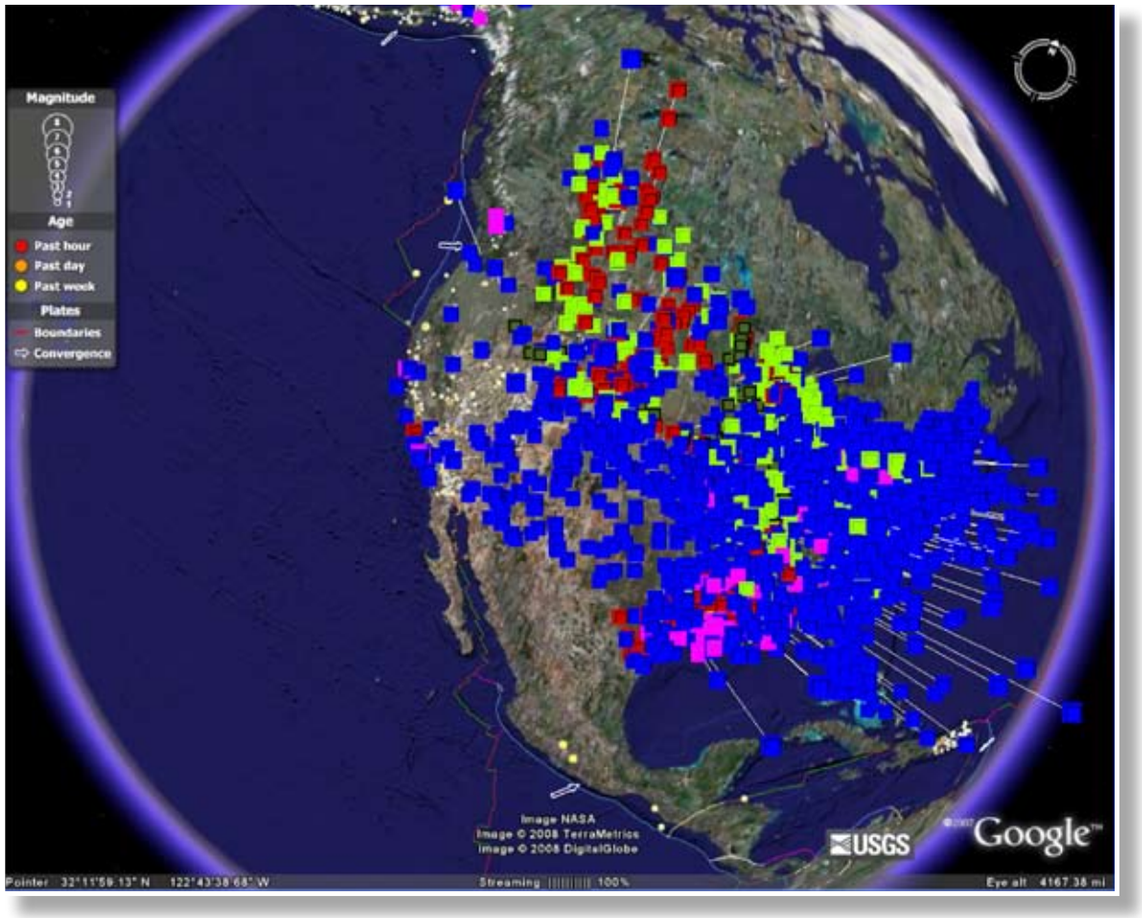
Southeast Regional Carbon Sequestration Partnership—The SECARB will conduct CO_2 injection tests at two locations. The Early Test will inject 1.4 million metric tons (1.5 million tons) of CO_2 from a natural source into the lower Tuscaloosa Formation Massive Sand Unit. The Anthropogenic Test will inject one million tons of CO_2 over a four-year period using CO_2 captured from a coal-fired power plant in the region. Extensive site characterization through drilling and geophysical logging has been performed at the Mississippi saline formation test site.

Southwest Regional Partnership for Carbon Sequestration—The SWP's large-scale test involves the injection of three million tons of CO_2 per year over a four-year period into the deep, Permian-aged White Rim sandstone in the Farnham Dome of Utah. The CO_2 will come from a natural CO_2 source in the Nugget Sandstone.

West Coast Regional Carbon Sequestration Partnership—The WESTCARB will perform an integrated CO_2 capture and storage test at the Kimberlina Test Facility in Kern County, California. The Partnership will inject one million tons of CO_2 over four years into a deep 2,000+ meter (7,000+ feet) geologic formation below a 50-MW, zero-emission power plant. The site is located at the southern end of the Great Central Valley, one of the largest CO_2 storage resources in WESTCARB's seven-state territory.

RCSP	Title	Geologic Formation	Depth (ft)	Source of CO_2	Volume to Inject (in metric tons CO_2/year)	Total Amount of CO_2 Injected (metric tons)
BSCSP	Large Volume Injection to Assess Commercial Scale Geological Sequestration in Saline Formations	Nugget Sandstone	11,000	Helium and Natural Gas Processing Plant	1,000,000	2,700,000
MGSC	Illinois Basin – Decatur Project	Mt. Simon Sandstone in the Illinois Basin	5,000–7,000	Ethanol Plant	365,000	1,000,000
MRCSP	Large Volume injection of CO_2 in Western Ohio	Mt. Simon Sandstone in the Cincinnati Arch	3,000–3,600	Ethanol Plant	250,000	1,000,000
PCOR	Williston Basin CO_2 Sequestration and EOR	Deep depleted oil fields in the Williston Basin, carbonate rocks	12,000	Post Combustion Capture Facility	1,000,000	5,000,000
	Fort Nelson CO_2 acid gas injection project	Sandstone in the Alberta Basin	5,000	Natural Gas Processing Plant	1,000,000	5,000,000
SECARB	SECARB Development Phase Saline Formation Demonstration - Cranfield	Sandstones of the lower Tuscaloosa Formation	10,500	Natural Source	1,000,000 for Early Test	1,500,000
	SECARB Development Phase Saline Formation Demonstration - Anthroprogenic	Tuscaloosa Formation Massive Sand Unit	9,500	Post Combustion Capture Facility	100,000 to 250,000	At least 400,000
SWP	Farnham Dome Deep Saline Deployment Project	Deep triassic, jurrassic, and permian aged sandstones in the Farnham Dome	5,000+	Natural Source	1,000,000	2,900,000
WESTCARB	Sequestration of CO_2 from OxyFuel Combustion Unit, Kern County, CA	A San Joaquin Basin sandstone formation	7000+	Oxycombustion Power Plant	250,000	1,000,000

* Information current as of 2008.



In 2009, NATCARB will provide CCS data, not only through high-end GIS and database query tools, but through simplified display for the general public employing readily available web tools such as Google Earth™ and Google Maps™. Images show locations of CO_2 emission sources, inventoried and accessible through the NATCARB portal, and displayed with Google Earth™. At the same time, images of geologic features and earthquakes from the U.S. Geological Survey are displayed. The experimental Google Earth™ NATCARB viewer is accessible through http://geoportal.kgs.ku.edu/NATCARB/basic_view/sources.cfm.

View of the experimental NATCARB Google Earth™ viewer.

National Carbon Sequestration Database and Geographical Information System

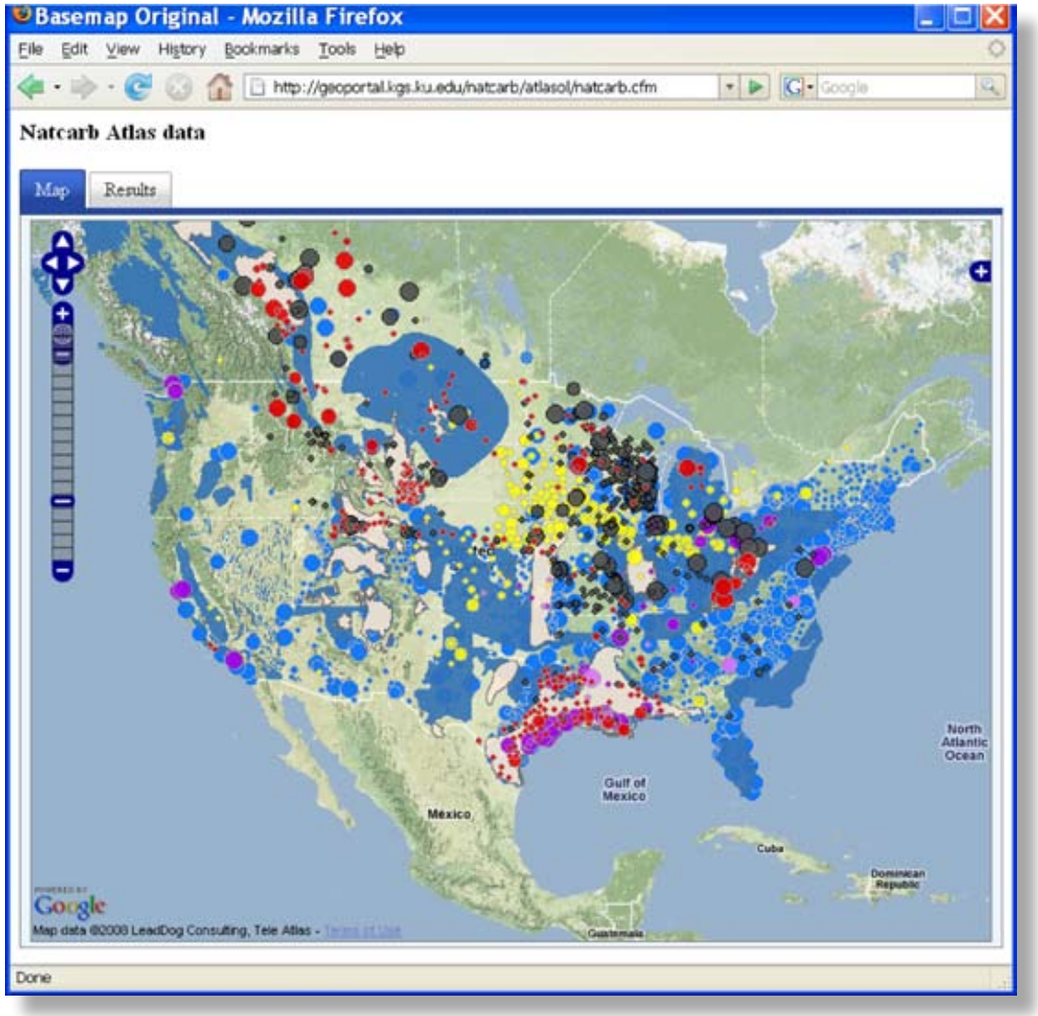
A National Look at Carbon Sequestration

The DOE's RCSPs generated the data for the maps displayed in this new version of the *Carbon Sequestration Atlas of the United States and Canada*. Key geospatial data (CO_2 emission sources, potential CO_2 storage sites, CO_2 transportation, land use, etc.) assembled through the National Carbon Sequestration Database and Geographical Information System (NATCARB) can assist in planning for efficient implementation of CCS on a national scale. NATCARB is a geographic information system (GIS) that integrates carbon sequestration data from the RCSPs and various other sources. The purpose of NATCARB is to provide a national view of the CCS potential in the U.S. and Canada. The digital spatial database allows users to estimate the amount of CO_2 emitted by sources (such as power plants, refineries, and other fossil-fuel-consuming industries) in relation to geologic formations that can provide safe CO_2 storage over long periods of time. NATCARB provides all stakeholders with improved online tools for the display and analysis of CO_2 capture and storage data.

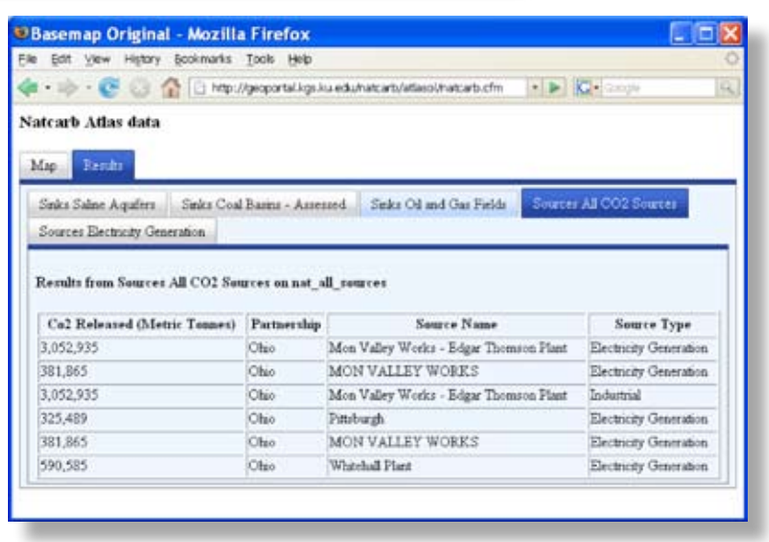
NATCARB organizes and enhances the critical information about CO_2 stationary emission sources and develops the technology needed to access, query, model, analyze, display, and distribute national CO_2 storage resource data for carbon management. Data are generated, maintained, and enhanced locally at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

NATCARB is a functional demonstration of distributed data-management systems that cross the boundaries between institutions and geographic areas. It forms the first step toward a functioning carbon sequestration information cyber-infrastructure. NATCARB online access has been modified to address the broad needs of a spectrum of users, and includes not only GIS and database query tools for the high-end technical user, but also simplified displays for the general public employing readily available web tools such as Google Earth™ and Google Maps™.

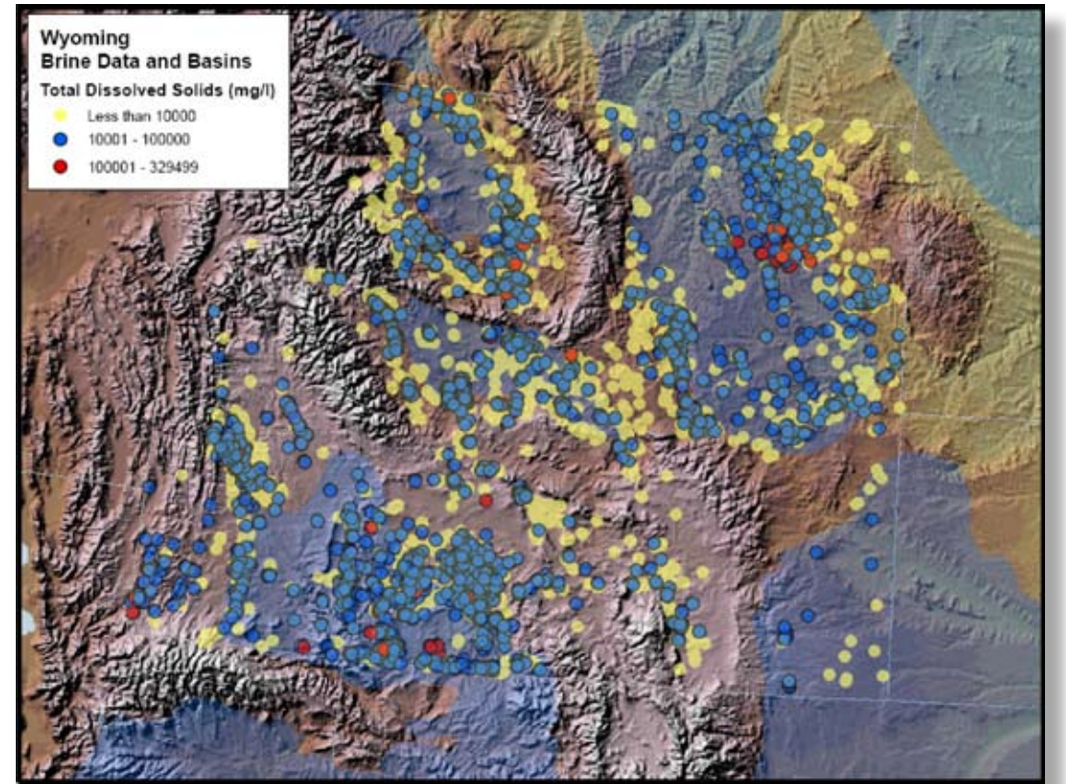
All map layers and data tables used to construct the national estimates of CO_2 stationary sources and geologic storage resources are available through interactive display and download through the NATCARB website http://www.NATCARB.org.



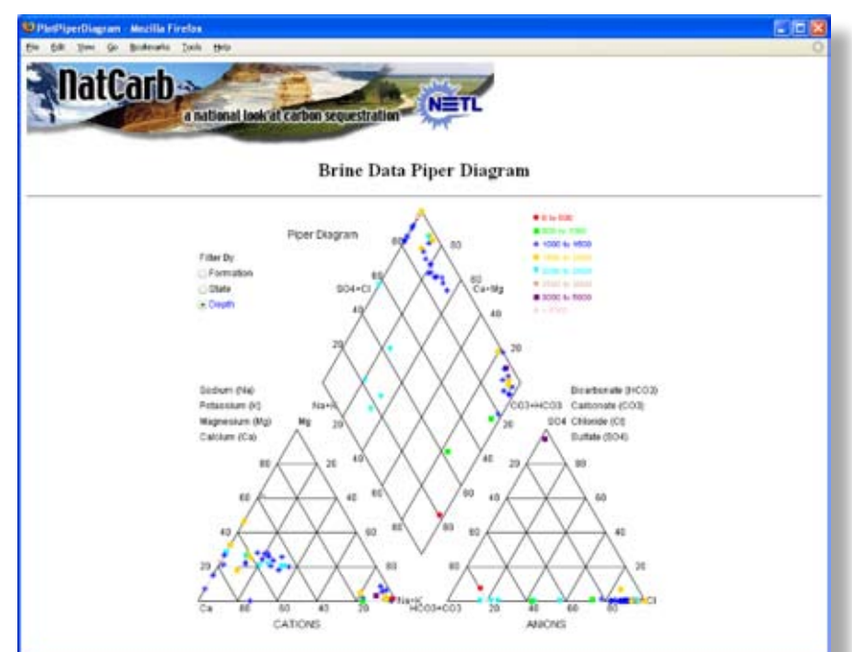
Example image of data accessible and displayed through NATCARB using Google Map™. This approach provides user-friendly access to national and regional information on CO_2 emission by sources (such as power plants, refineries, and other fossil-fuel-consuming industries) in relation to geologic formations that can provide safe CO_2 storage over long periods of time. Data can be queried to provide access to tabular data (see figure at right).



Co2 Released (Metric Tonnes)	Partnership	Source Name	Source Type
3,052,935	Ohio	Mon Valley Works - Edgar Thomson Plant	Electricity Generation
381,865	Ohio	MON VALLEY WORKS	Electricity Generation
3,052,935	Ohio	Mon Valley Works - Edgar Thomson Plant	Industrial
325,489	Ohio	Pittsburgh	Electricity Generation
381,865	Ohio	MON VALLEY WORKS	Electricity Generation
590,585	Ohio	Whitehall Plant	Electricity Generation



Regional data on potential CO_2 geologic storage sites can be assembled and displayed through NATCARB. The image above shows the distribution of locations in Wyoming with over 15,000 water samples from brine formations. Data are categorized by total dissolved solids (TDS). Samples with less than 10,000 mg/l TDS are considered potentially potable water and need to be protected (yellow dots). Formations containing TDS concentrations above 10,000 mg/l are sites that merit further evaluation for potential CO_2 storage (blue and red dots). Basins containing brine formations that have been evaluated are highlighted in blue. Data on brine geochemistry can be accessed and summarized with several additional online tools (see figure below). All data were assembled through NATCARB.



Methodologies Used to Estimate CO_2 Stationary Source Emissions and CO_2 Geologic Storage Potential

CO_2 Stationary Source Emissions Summary

Introduction

The Capture Working Group of DOE's Regional Carbon Sequestration Partnerships (RCSPs) summarized the calculations, emissions factors, and databases employed by the RCSPs with respect to CO_2 stationary source emissions estimation methods (Appendix A: CO_2 Stationary Source Emission Estimation Methodologies Summary). Carbon dioxide stationary sources include power plants, ethanol plants, petroleum and natural gas processing facilities, cement and lime plants, and the following facilities: agricultural processing, industrial, iron and steel production, and fertilizer-producing. Estimation methods include the use of databases and emissions factors which are listed by CO_2 source type in Appendix A.

The documents used to identify each CO_2 stationary source, as well as the practical quantitative method (e.g., emission factors, continuous emissions-monitoring results, emission estimate equations) used to estimate CO_2 emissions from a particular source, are listed in the "CO_2 Emissions Methodology References" section of Appendix A. The data sources used to determine specific plant capacities, production outputs, or fuel usage data are listed by RCSP in the "Data References by Partnership and Industry" section of Appendix A.

Approach

The approach for determining these methodologies was to first identify significant CO_2 emission sources within each Region, and then to assess the availability of CO_2 emission data or to apply an estimate of the CO_2 emissions based upon sound scientific and engineering principles. In each RCSP, the emissions were grouped by emission source, and a methodology was established for each emission source category; the methodology was then utilized to estimate the CO_2 emissions from each emission source category. To summarize these efforts, nine tables containing CO_2 emission estimation methodology and equations for the major CO_2 stationary source industries have been created. Each RCSP was responsible for developing GHG emission inventories and stationary source surveys within their respective Region. Approximately 4,800 stationary sources have been documented for the seven RCSPs.

CO_2 Estimation Methodology

For any stationary source within a given industry type, the RCSPs employed CO_2 emissions estimate methodologies that are based on the most readily available representative data for that particular industry type within the respective Region. CO_2 emissions data provided by databases (such as Emissions & Generation Resource Integrated Database [eGRID], ECOFYS, and others) were the first choice for all of the RCSPs, both for identifying major CO_2 stationary sources and for providing reliable emission estimates. These databases are considered to contain reliable and accurate data obtained from direct emissions measurements via continuous emissions monitoring systems. One drawback of formal databases can be the delay between data collection and data publication, but this does not present a significant problem for the RCSPs as the dates of information are clear. When databases were not available, stationary source facility production or fuel usage were coupled with CO_2 emissions factors to estimate annual CO_2 emissions from the production or fuel usage data. Emissions factors, fuel usage data, and facility production data were obtained from various databases, websites, and publications. 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 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 U.S. Geological Survey's Digital Orthophoto Imagery) equipped with geospatially defined data, along with web-based databases (Travelpost) containing latitude and longitude information for various U.S. locations.

Methodology for Development of Geologic Storage Estimates for Carbon Dioxide

Introduction

The "Methodology for Development of Geologic Storage Estimates for Carbon Dioxide" (Appendix B) is an update to the 2006 "Methodology for Development of Carbon Sequestration Capacity Estimates" published in the *2007 Carbon Sequestration Atlas of the United States and Canada (Atlas I)*. The Capacity and Fairways Subgroup, convened by the Geologic Working Group for the RCSPs, lead this effort to describe the methodologies used to produce the geologic storage resource estimates for CO_2 in the *2008 Carbon Sequestration Atlas of the United States and Canada (Atlas II)*. The peer-reviewed methodologies represent simplified assumptions used to estimate the amount of CO_2 that can be stored in subsurface geologic environments of the United States and parts of Canada.

The Capacity and Fairways Subgroup includes representatives from DOE, each RCSP, NATCARB, the CSLF, and multiple State Geological Surveys.

The RCSPs are charged with providing a quantitative estimate of the geologic storage resource for CO_2 in the subsurface environments of their regions. These estimates are necessary to indicate the extent to which CCS technologies could contribute to the reduction of CO_2 emissions into the atmosphere. This assessment is a high-level overview and is not intended as a substitute for site-specific assessment and testing. The methodologies described were designed to integrate results of data compiled by the seven RCSPs for three types of geologic formations: saline formations, unmineable coal seams, and oil and gas reservoirs. These methodologies are developed to be consistent across North America for a wide range of available data. Results of this assessment are intended to be distributed by a GIS and are available as hard-copy results in *Atlas II*.

Atlas II provides CO_2 ***storage resource*** estimates by state/province and RCSP. Methodologies presented describe calculations and assumptions used for CO_2 **storage resource** estimates. A CO_2 ***storage 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 **storage resource** assessments do not include economic or regulatory constraints; only physical constraints to define the accessible part of the subsurface are applied. Economic or regulatory constraints are included in CO_2 ***capacity*** estimates. It should also be noted that for the development of specific commercial-scale geologic storage sites, economic and regulatory constraints must be considered to determine the portion of the CO_2 storage resource that is available under various development scenarios. Under the most favorable economic and regulatory scenarios, 100 percent of the estimated CO_2 **storage resource** may be considered CO_2 **capacity**.

Methods for estimating subsurface volumes are widely and routinely applied in petroleum, groundwater, underground natural gas storage, and Underground Injection Control disposal-related estimations. Therefore, the volumetric method is the basis for CO_2 storage resource calculations in *Atlas II*. The volumetric formula uses porosity, area, and thickness in a Monte Carlo simulation approach with various efficiency terms included to account for ranges of variations in the geologic volumetric properties and the fraction of the accessible pore volume that is most likely to be contacted by injected CO_2.

Types of Geologic Environments

For the purposes of this assessment, the subsurface is categorized into five major geologic formations: saline formations, coal seams, oil and gas reservoirs, shale, and basalt formations. Each of these is defined and input parameters for CO_2 storage resource calculations are described in Appendix B. Carbon dioxide storage resource has been quantified where possible for saline, coal, oil, and gas, whereas shale and basalt formations are presented as future opportunities and not assessed in this document.

SALINE FORMATION CO_2 STORAGE RESOURCE ESTIMATING

Saline formations are composed of porous rock saturated with brine and capped by one or more regionally extensive impermeable rock formations enabling trapping of injected CO_2. A saline formation assessed for storage is defined as a porous and permeable body of rock containing water with total dissolved solids (TDS) greater than 10,000 parts per million (ppm), which can store large volumes of CO_2. A saline formation can include more than one named geologic formation or be defined as only part of a formation. Saline formations have the largest CO_2 storage resource potential and are widespread throughout the United States and Canada.

OIL AND GAS RESERVOIR CO_2 STORAGE RESOURCE ESTIMATING

Typical mature oil and gas reservoirs in North America have held crude oil and natural gas over millions of years. They consist of a layer of permeable rock with a layer of nonpermeable rock (caprock) above, such that the nonpermeable layer forms a trap that holds the oil and gas in place. Oil and gas fields have many characteristics that make them excellent target locations for geologic storage of CO_2. The geologic conditions that trap oil and gas are also the conditions that are conducive to long-term CO_2 storage.

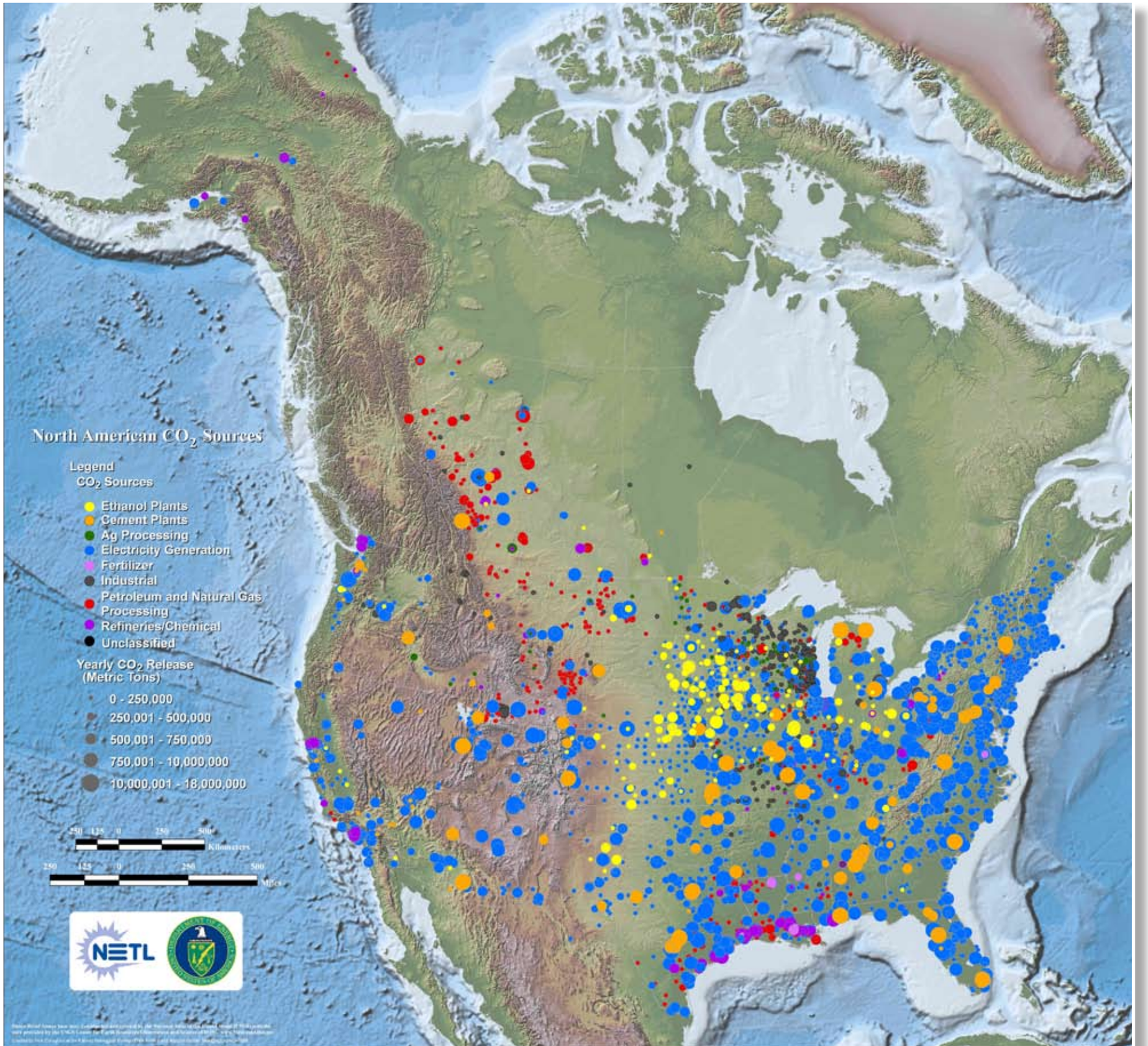
As a value-added benefit, CO_2 injected into a mature oil reservoir can enable incremental oil to be recovered. A small amount of CO_2 will dissolve in the oil, increasing its bulk volume and decreasing its viscosity, thereby facilitating flow to the wellbore. Typically, primary oil recovery and secondary recovery via a water flood produce 30-40 percent of a reservoir's original oil-in-place (OOIP). Enhanced Oil Recovery (EOR) via a CO_2 flood allows recovery of an additional 10-15 percent of the OOIP.

COAL SEAM CO_2 STORAGE RESOURCE ESTIMATING

Carbon dioxide storage opportunities exist within coal seams. All coals have varying amounts of methane adsorbed onto pore surfaces, and wells can be drilled into unmineable coalbeds to recover this coalbed methane (CBM). Initial CBM recovery methods, such as dewatering and depressurization, leave a considerable amount of methane in the formation. Additional recovery can be achieved by sweeping the coalbed with CO_2. Depending on coal rank, as few as 3 to as many as 13 molecules of CO_2 may be adsorbed for each molecule of methane released, thereby providing an excellent storage site for CO_2 along with the additional benefit of enhanced coalbed methane (ECBM) recovery.

Results

A summary of the National CO_2 storage resource estimates computed by each RCSP and compiled by NATCARB appears in the "National Perspectives" section of *Atlas II*. Regional details of these CO_2 storage resource estimates appear in the "Regional Carbon Sequestration Partnerships Perspectives" section of *Atlas II*. Lastly, a State summary of CO_2 storage resource estimates appears in Appendix C of *Atlas II*.



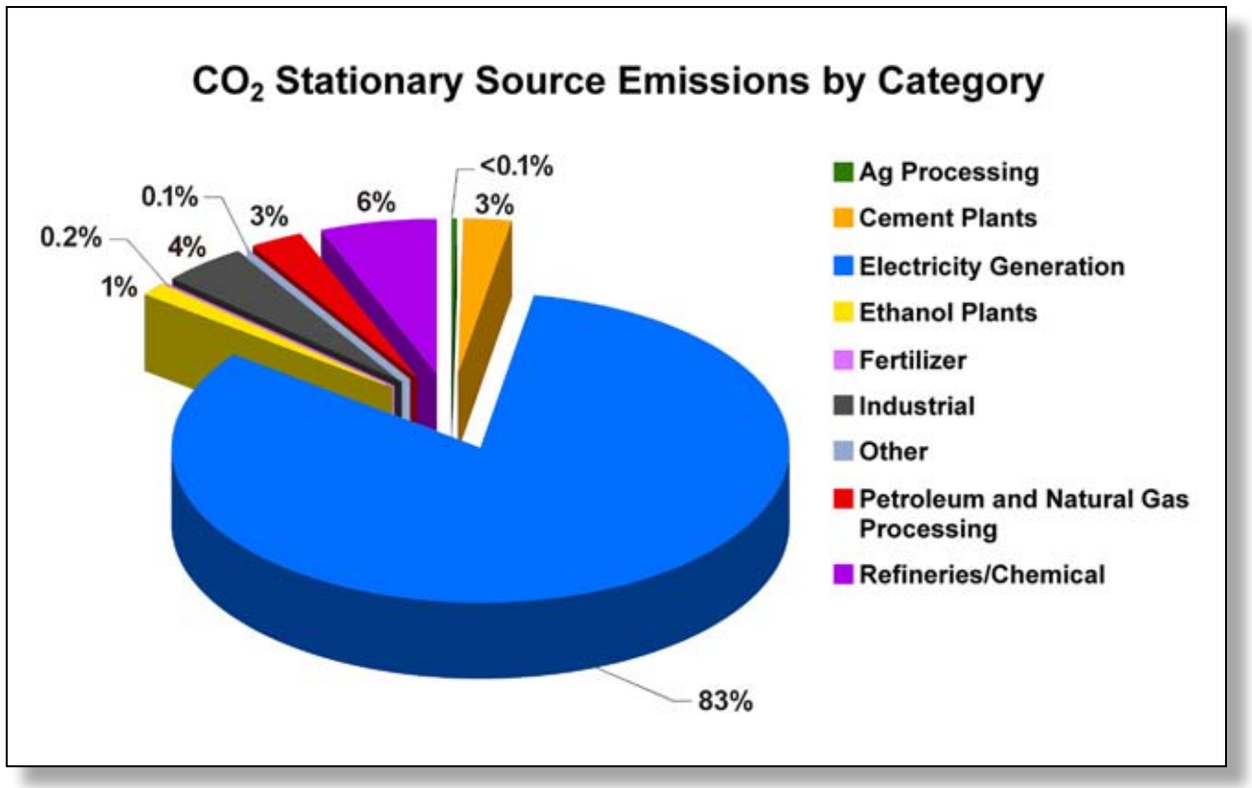
This map displays stationary source data which were obtained from the RCSPs and other external sources and compiled by NATCARB. Each colored dot represents a different type of stationary source with the dot size representing the relative magnitude of the CO_2 emission source (see map legend).

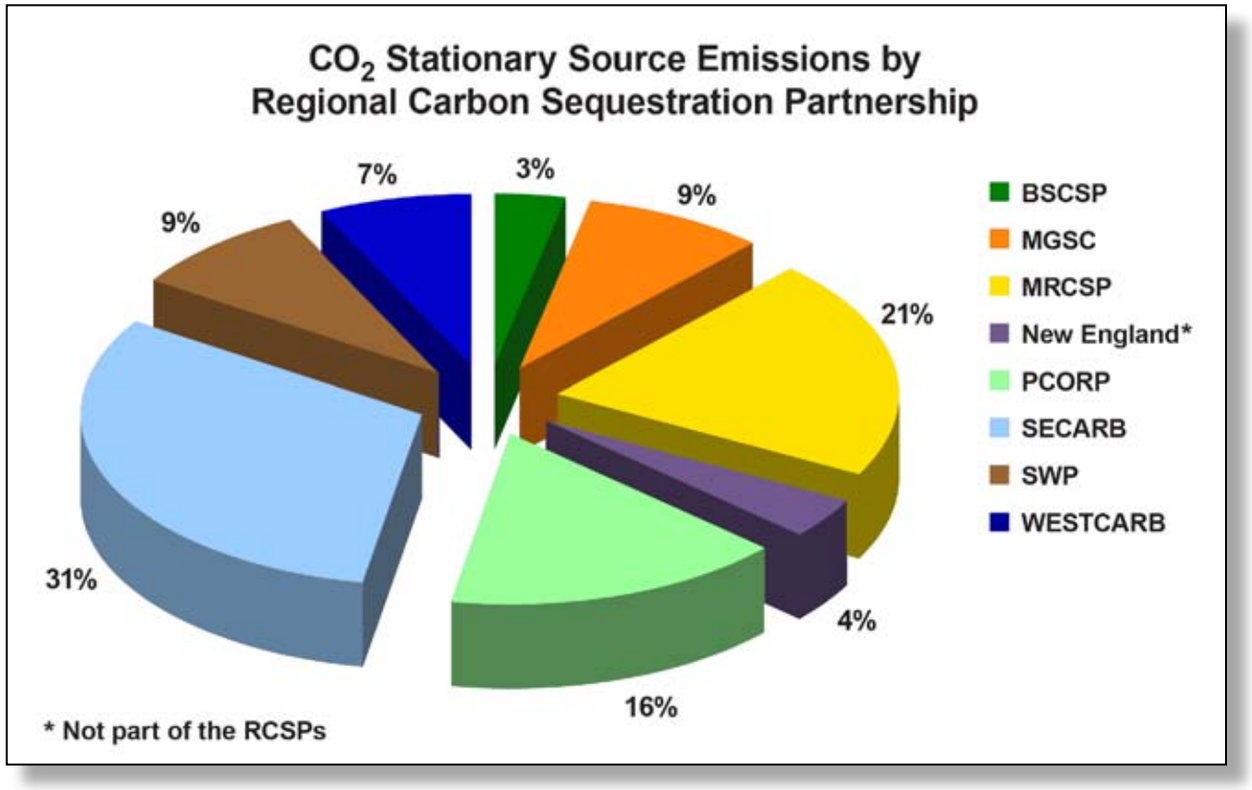
Carbon Dioxide Sources

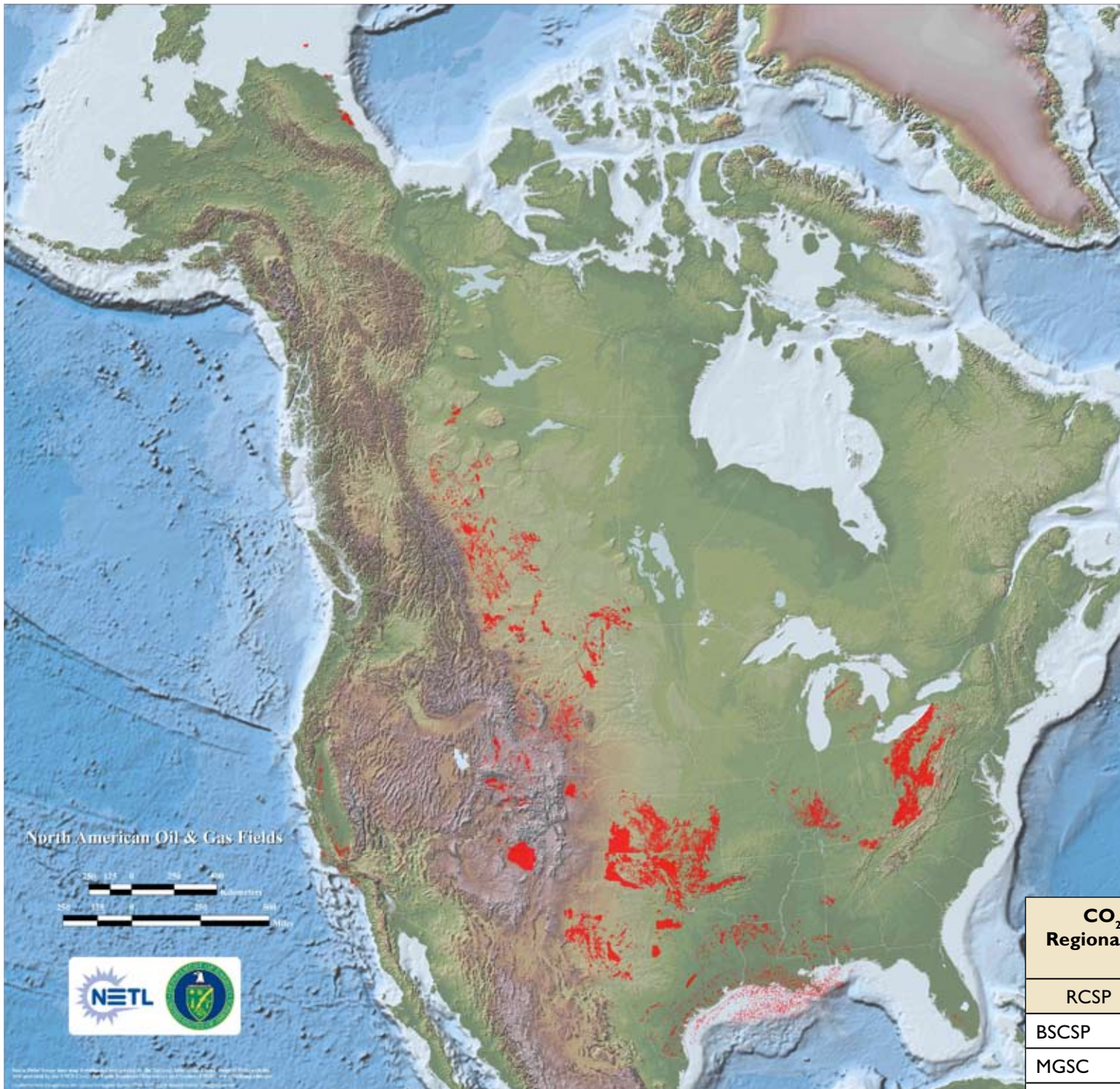
There are two types of CO_2 emission sources: stationary sources and non-stationary sources. Non-stationary source emissions include CO_2 emissions from the transportation sector (vehicles, railroads, airplanes, etc.). Stationary source emissions come from a particular, identifiable, localized source, such as a power plant. Carbon dioxide from stationary sources can be separated from plant emissions and subsequently transported to a geologic storage injection site. The "North American CO_2 Sources" map displays the location and relative magnitude of a variety of CO_2 stationary sources.

According to the EPA in 2006, total U.S. GHG emissions were estimated at 7,100 million metric tons (7,800 million tons) CO_2 equivalent. This estimate included CO_2 emissions as well as other GHGs such as methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs). Annual GHG emissions from fossil fuel combustion, primarily CO_2, were estimated at 5,600 million metric tons (6,200 million tons) with 3,800 million metric tons (4,200 million tons) from stationary sources.

The "CO_2 Stationary Source Emissions by Category" pie chart (top right) contains values, gathered by the RCSPs and compiled by NATCARB (illustrated on the "North American CO_2 Sources" map), showing that CO_2 stationary source emissions result largely from electric power generation, energy use, and industrial processes. While not all potential GHG sources have been examined, NETL's RCSPs have documented the location of more than 4,600 stationary sources with total annual emissions of over 3,200 million metric tons (3,600 million tons) of CO_2. The "CO_2 Stationary Source Emission by Regional Carbon Sequestration Partnership" pie chart (bottom right) displays the amount of CO_2 stationary source emissions identified by each RCSP. For details on sources by state, see Appendix C.







This map displays oil and gas reservoir data which were obtained by the RCSPs and other sources and compiled by NATCARB.

Oil and Gas Reservoirs

Mature oil and gas reservoirs have held crude oil and natural gas for millions of years. The reservoirs consist of a layer of permeable rock with a layer of nonpermeable rock (caprock) above, such that the nonpermeable rock layer forms a trap that holds the oil and gas in place. Oil and gas reservoirs have many characteristics that make them excellent target locations for geologic storage of CO_2. The geologic conditions that trap oil and gas are also the conditions that are conducive to CO_2 sequestration.

As a value-added benefit, when CO_2 is injected into a mature oil reservoir, it can produce additional oil. This process, enhanced oil recovery (EOR), begins by injecting CO_2 into an oil reservoir. A small amount of the injected CO_2 dissolves in the oil, increasing the bulk volume and decreasing the viscosity, thereby facilitating flow to the wellbore. Carbon dioxide injection allows recovery of an additional 10–15 percent of the oil. NETL's work in this area is focused on increasing the amount of CO_2 that remains in the ground as part of CO_2 EOR injection.

While not all potential mature oil and gas reservoirs in all states and provinces have been examined, the RCSPs have documented the location of 138 billion metric tons (152 billion tons) of geologic CO_2 storage potential in more than 10,000 oil and gas reservoirs distributed over 27 states and 3 provinces. This is an increase of approximately 56 billion metric tons (62 billion tons) of identified CO_2 storage potential from the previous version of the *Atlas*. For details on oil and gas storage by state, see Appendix C.

CO_2 Storage Resource Estimates by Regional Carbon Sequestration Partnership for Oil and Gas Reservoirs

RCSP	Billion Metric Tons	Billion Tons
BSCSP	1.5	1.6
MGSC	0.4	0.4
MRCSP	8.4	9.3
PCOR	24.1	26.5
SECARB	31.1	34.3
SWP	65.0	71.7
WESTCARB	7.7	8.5
TOTAL	138	152

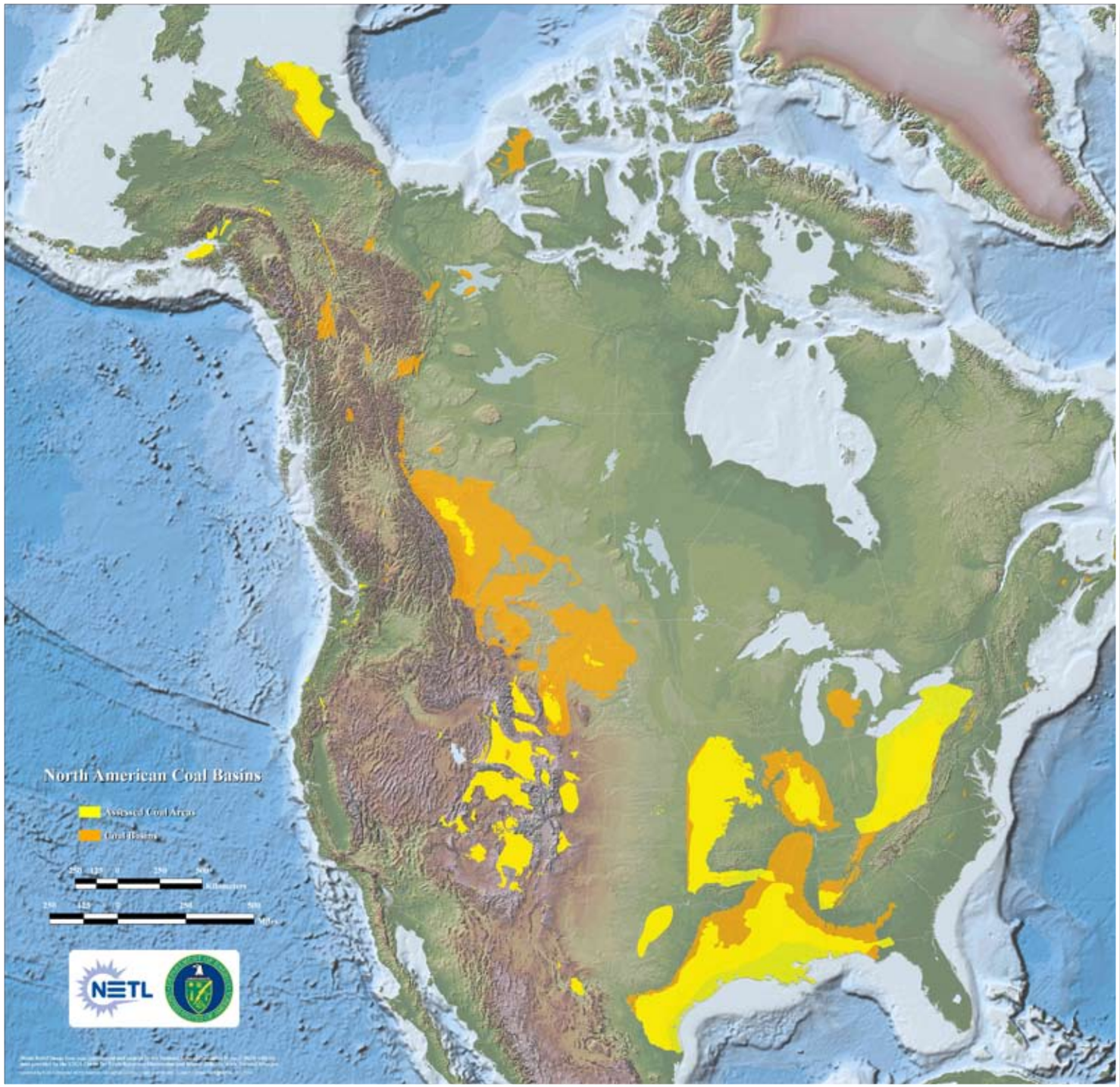
Unmineable Coal Seams

Unmineable coal seams are too deep or too thin to be economically mined. All coals have varying amounts of methane adsorbed onto pore surfaces, and wells can be drilled into unmineable coalbeds to recover this coalbed methane (CBM). Initial CBM recovery methods, such as dewatering and depressurization, leave a considerable amount of methane in the formation. Additional recovery can be achieved by sweeping the coalbed with CO_2. Depending on the type of coal, a variable amount of methane is released, thereby providing an excellent storage site for CO_2 along with the additional benefit of enhanced coalbed methane (ECBM) recovery. Similar to maturing oil reservoirs, unmineable coalbeds are good candidates for CO_2 storage.

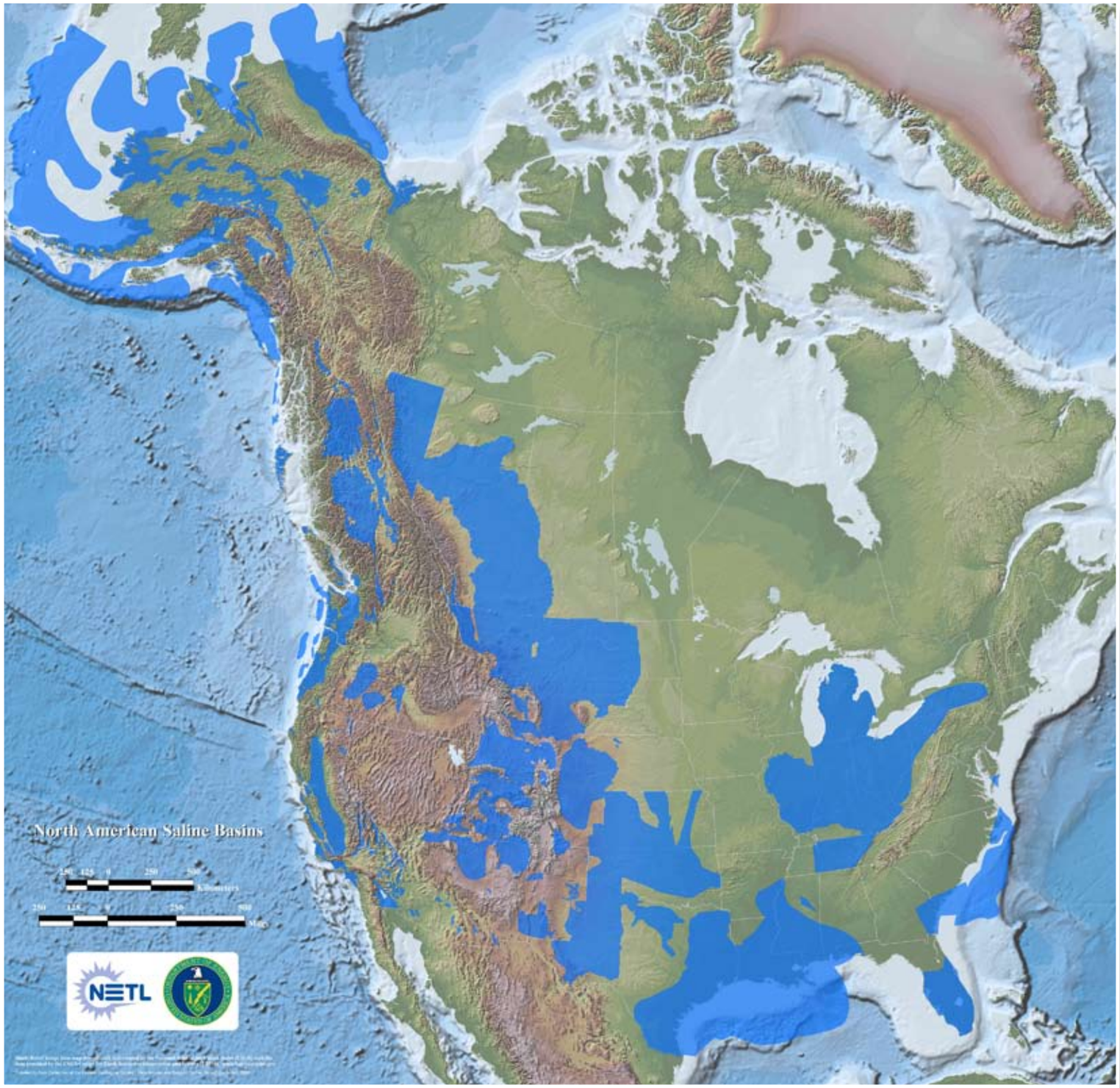
While not all potential areas of unmineable coal have been examined, the RCSPs have documented the location of 157–178 billion metric tons (173–196 billion tons) of CO_2 geologic storage potential in unmineable coal seams distributed over 24 states and 3 provinces. This is an increase of approximately 1 billion metric tons (1.1 billion tons) of identified storage from the previous version of the *Atlas*. For details on unmineable coal seam storage by state, see Appendix C.

CO_2 Storage Resource Estimates by Regional Carbon Sequestration Partnership for Unmineable Coal Seams

	Low		High	
RCSP	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	12.1	13.3	12.1	13.3
MGSC	1.7	1.8	2.4	2.6
MRCSP	0.8	0.9	0.8	0.9
PCOR	10.7	11.8	10.7	11.8
SECARB	43.8	48.3	63.0	69.4
SWP	0.7	0.8	1.8	2.0
WESTCARB	86.8	95.7	86.8	95.7
TOTAL	157	173	178	196



This map displays coal basin data which were obtained by the RCSPs and other sources and compiled by NATCARB.



This map displays saline formation data which were obtained by the RCSPs and other sources and compiled by NATCARB.

Deep Saline Formations

Saline formations are layers of porous rock that are saturated with brine. They are much more extensive than coal seams or oil- and gas-bearing rock, and represent an enormous potential for CO_2 geologic storage. However, much less is known about saline formations because they lack the characterization experience that industry has acquired through resource recovery from oil and gas reservoirs and coal seams. Therefore, there is a greater amount of uncertainty regarding the suitability of saline formations for CO_2 storage.

While not all saline formations in the U.S have been examined, the RCSPs have documented the locations of saline formations with an estimated CO_2 sequestration potential ranging from 3,300 to more than 12,000 billion metric tons (from 3,600 to more than 13,000 billion tons). This is an increase of 2,000 to 9,000 billion metric tons (2,200 to 10,000 billion tons) of identified CO_2 storage from the previous version of the *Atlas*. For details on deep saline formation storage by state, see Appendix C.

CO_2 Storage Resource Estimates by Regional Carbon Sequestration Partnership for Saline Formations

	Low		High	
RCSP	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	460.9	508.0	1,831.5	2018.9
MGSC	29.2	32.1	116.6	128.6
MRCSP	49.6	54.7	199.1	219.5
PCOR	185.6	204.6	185.6	204.6
SECARB	2,274.6	2,507.3	9,098.4	10029.3
SWP	92.4	101.9	368.9	406.6
WESTCARB	204.5	225.4	818.2	901.9
TOTAL	3,297	3,634	12,618	13,909

Future Geologic Sequestration Options

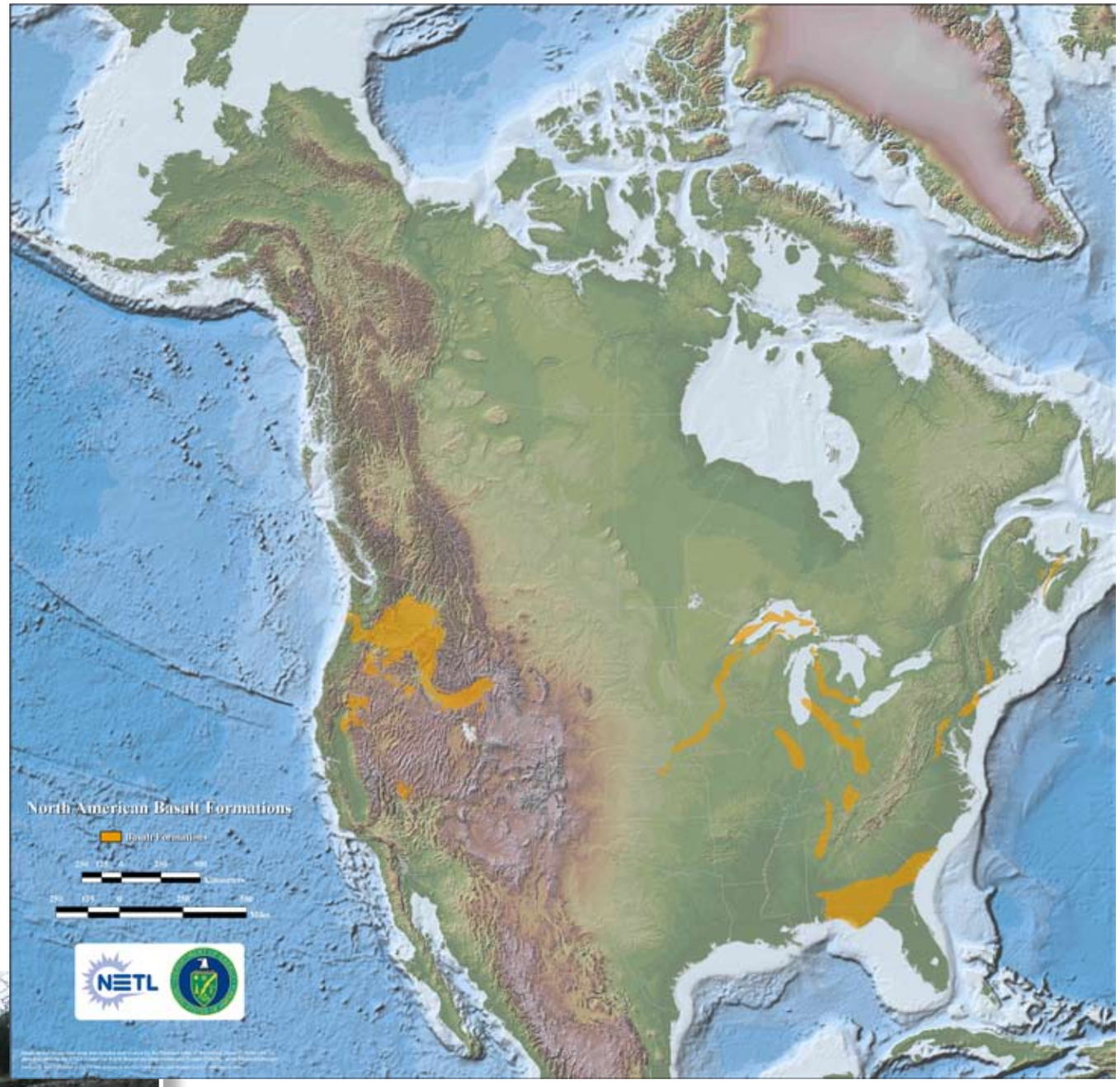
Other possible geologic sequestration options include basalts and shale formations.

Basalt Formations

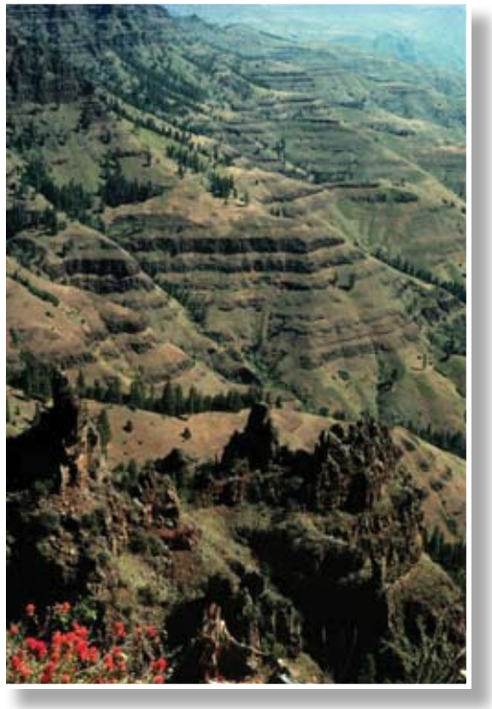
Basalt formations are geologic formations of solidified lava. Basalt formations have a unique chemical makeup that could potentially convert all of the injected CO_2 to a solid mineral form, thus isolating it from the atmosphere permanently. Research is focused on enhancing and utilizing the mineralization reactions and increasing CO_2 flow within a basalt formation.

Organic Rich Shales

Shale, the most common type of sedimentary rock, is characterized by thin horizontal layers of rock with very low permeability in the vertical direction. Many shales contain 1–2 percent organic material in the form of hydrocarbons, which provide an adsorption substrate for CO_2 storage similar to CO_2 storage in coal seams. Research is focused on achieving economically viable CO_2 injection rates, given the shales' low permeability.



This map displays basalt formation data which were obtained from the RCSPs and other external sources and compiled by NATCARB.



Columbia River Basalt.

Devonian Ohio shale in Eastern Kentucky.

Terrestrial Sequestration

Terrestrial sequestration is CO_2 uptake by soils and plants, both on land and in aquatic environments such as wetlands and tidal marshes. Terrestrial sequestration provides an opportunity for low-cost atmospheric CO_2 reductions and usually offers additional benefits such as habitat and/or water quality improvements. Terrestrial CO_2 sequestration efforts include tree-plantings, no-till farming, wetlands restoration, land management on grasslands and grazing lands, fire management efforts, and forest preservation. More advanced research includes the development of fast-growing trees and grasses and deciphering the genomes of carbon-storing soil microbes. NETL's Program efforts in the area of terrestrial sequestration include a focus on increasing carbon uptake on mined lands and quantifying sequestration benefits of growing biomass for power generation. These activities complement research into afforestation and agricultural practices that are being led by the U.S. Department of Agriculture (USDA). The U.S. DOE's Office of Science, the U.S. EPA, and the Department of the Interior are also involved in terrestrial sequestration in supporting and complementary roles.

The RCSPs are implementing 11 terrestrial sequestration field projects during the Validation Phase on abandoned mine land, wetlands, agricultural fields, prairie lands, and forests to validate the best practices for the enhancement of these sinks to store carbon emitted from distributed sources such as automobiles. The projects are measuring the effects on carbon storage from reclaiming damaged lands and altering land-use management practices which are designed to increase the storage rate in above and below ground carbon stocks and reduce the release of stored carbon by minimizing disturbance to the soils. Many of these projects will help to develop the MVA protocols to allow the carbon stored in these terrestrial ecosystems to be credited as greenhouse gas emissions reduction on future trading markets.

United States Geological Survey

Development of Refined Geologic Carbon Sequestration Assessment Methodology

Complementing the approach used in this *Atlas*, the U.S. Geological Survey (USGS) is using USGS experience with oil and gas resource assessment to develop a methodology to quantify geologic storage capacity for CO_2. This methodology development, mandated by the Energy Independence and Security Act of 2007, will allow refinement of the estimates presented in this *Atlas* as well as incorporation of uncertainty in capacity estimates. Having refined estimates will assist policy and decision makers in the future as they address mitigation strategies for global climate change.

The quantitative and probabilistic USGS resource assessment methodology will evaluate CO_2 storage resources in oil and gas reservoirs and saline formations. Storage in unmineable coal seams, which is included in the resource estimates of this *Atlas*, will not be addressed in this initial USGS methodology. Other potential storage reservoirs, such as organic-rich shales and terrestrial storage, are also excluded at this time. It should be noted that the product of the current USGS work is a methodology only. Substantial additional work would be required to apply the USGS methodology to all of the areas evaluated in this *Atlas*.

The assessment methodology will build upon the principles of USGS geologic oil and gas resource evaluation and assessment (Klett et al., 2003; Schmoker and Klett, 2003; Charpentier and Klett, 2003). This methodology has been extensively peer-reviewed (American Association of Petroleum Geologists Committee on Resource Evaluations (CORE) Subcommittee, 1999, 2000) and has been applied in a standardized manner to domestic and international basins and provinces. The methodology will produce probabilistic volume calculations based upon volume ranges (sizes and numbers of fields) and uncertainties as well as integrated risk factors (e.g., integrity of seals on local and regional scales, formation water displacement). It will define critical parameters necessary to determine geologic CO_2 sequestration reserves. The USGS methodology is being developed by an integrated and complementary team of geologists, hydrologists, geochemists, and assessment methodology scientists.

Two assessment unit test cases are underway to develop and evaluate the methodology: the Tensleep Formation (storage) and Phosphoria and Park City Formations (seal) in the Wind River Basin of Wyoming; and the Frio Formation (storage) and Anahuac Formation (seal) of the Gulf Coastal Plain of Texas. These test cases were selected because storage formations and seals can be evaluated as an integrated storage assessment unit. Data relevant to storage in the depth range of 1–4 km are available from proprietary databases, State surveys and agencies, oil and gas operators, and published sources to estimate storage efficiency, reactivity of aqueous phases, and regional flow of formation water.

For each test case, geologic and hydrogeochemical frameworks will be based on work completed for the USGS National Oil and Gas Assessment project and regional groundwater flow studies. The geologic framework will be based on stratigraphy, depositional environments, diagenetic history, mineralogy of storage areas and seals, structural history, and types of known traps. Input parameters for the hydrogeochemical framework will include formation water chemistry, information on regional flow systems, evidence for compartmentalization, drive mechanisms for hydrocarbon production, and predicted reactivity of formation water, seals, and storage units to CO_2.

Another important part of the methodology will be the identification of risk factors. Risk factors will be evaluated on a numeric scale and independent risks will be combined mathematically to determine the overall risk of storage in traps and saline formations. Risks include those identified in the methodology used in this *Atlas*: (1) seal integrity based on petroleum geochemistry, seal thickness and homogeneity, presence of faults, potential for seismic activity, and hydrologic regime; and (2) seal capacity estimated from known hydrocarbon column heights and capillary injection pressures. However, there are other risk factors that will be identified as the methodology develops, such as limits on injectivity and potential displacement of formation water into shallow aquifers. The results of the test cases will be probabilistic ranges of the storage capacity in traps (oil and gas reservoirs) and in the saline formation of the assessment unit. The numeric risk factor will then be used to adjust the ranges of storage capacity for level of risk.

In summary, the USGS is developing a peer-reviewed methodology that will allow refinement of the CO_2 storage resource estimates presented in this *Atlas*. The USGS and DOE are cooperating in this effort in order to provide policy makers with increasingly reliable information for climate-change-relevant policy discussions and decisions.

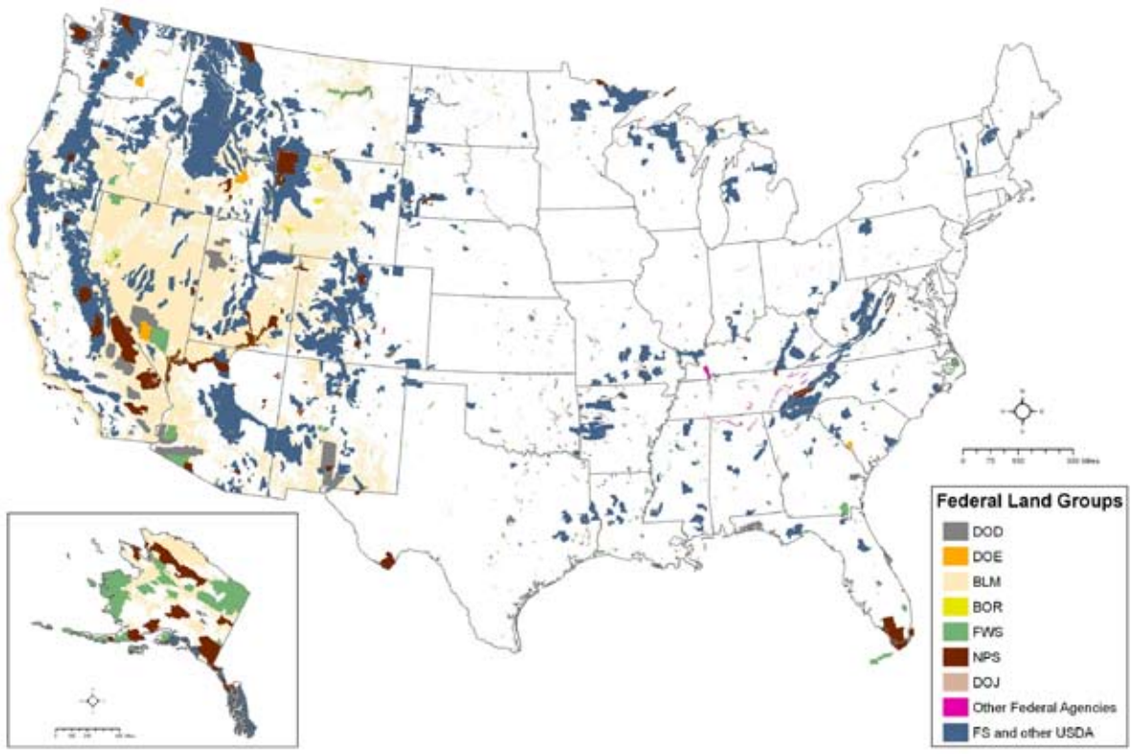


Figure 1. Federal Land Groups

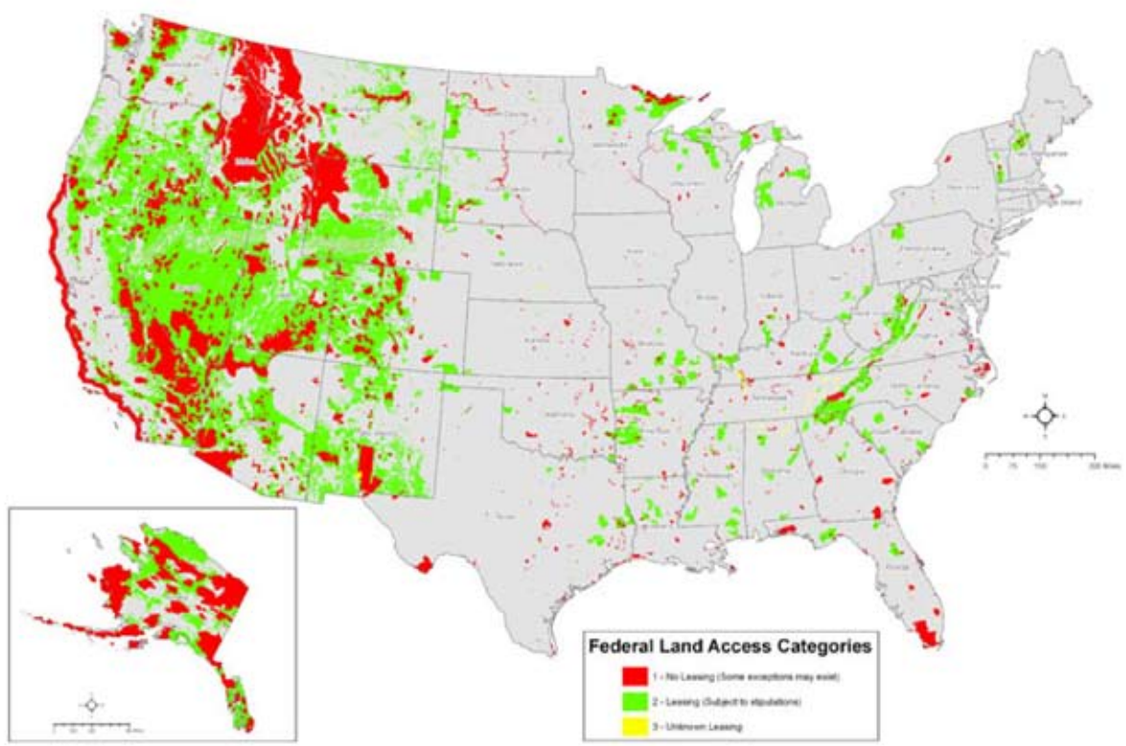


Figure 2. Federal Land Access Categories

Federal Land

Land Management

The Federal Government owns about 2.91 million km^2 (1.13 million mi^2) of land, almost 30 percent of the total U.S. land mass. A recent study used an existing USGS spatial shapefile to identify lands owned and/or administered by the Federal Government. The source dataset categorizes Federal landholdings under 65 separate government bodies. However, to obtain a manageable description of Federal landholdings, these 65 categories were reorganized into 9 land groups according to common Department or Agency (see Figure 1): (1) Department of Defense (DOD); (2) DOE; (3) Bureau of Land Management (BLM); (4) Bureau of Reclamation (BOR); (5) U.S. Fish and Wildlife Service (FWS); (6) National Park Service (NPS); (7) Department of Justice (DOJ); (8) other Federal Agencies; and (9) U.S. Forest Service (FS) and other USDAs. The BLM and the FWS, both in the Department of Interior (DOI), and the FS, of the Department of Agriculture, manage the vast majority of Federal acreage—about 2.45 million km^2 (0.95 million mi^2).

An assessment of Federal leases with respect to oil and gas resources, per Section 364 of the Energy Policy and Conservation Act (EPCA) of 2005, was recently completed by the DOI. Utilizing this study, it was recognized that certain agencies do not lease or are restricted from leasing lands under their management—for example NPS or FWS lands—and a net value of 1.62 million km^2 (0.63 million mi^2) was derived. This distribution is illustrated in Figure 2.

The BLM and the FS manage almost 99 percent of the leasable lands, 1.60 million km^2 (0.62 million mi^2), the vast majority of which is located in the Rocky Mountain States and further west. Potentially leasable lands from the BLM and FS are listed in Table 1. Additional restrictions may be added for the protection of wildlife and ecosystems as described in the study.

Table 1. Leasable Federal Lands (million km^2)

RCSP	BLM	USFS	*Total*
BSCSP	0.11	0	0.11
MGSC	0	0.01	0.01
MRCSP	0	0.04	0.04
PCOR	0.03	0.08	0.11
SECARB	0	0.08	0.08
SWP	0.17	0.16	0.33
WESTCARB	0.64	0.28	0.92
TOTAL	0.95	0.65	1.60

CO_2 Storage Resource

The estimated CO_2 storage resource beneath leasable Federal Lands is between 127 and 374 billion metric tons (140 and 412 billion tons) (Table 2). This is about 5.5 percent of the onshore CO_2 storage resource presented in this *Atlas*.

Table 2. CO_2 Storage Resource Beneath Federal Lands

	Low		High	
	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
Oil & Gas	32	35	32	35
Coal	4	5	5	6
Saline	91	100	337	371
TOTAL	127	140	374	412

A third of the potential CO_2 storage resource for oil and gas reservoirs is found beneath Federal Lands. Only 2.5–5 percent of the CO_2 storage resource for unmineable coal seams and saline formations can be found beneath Federal Lands. These values and percentages represent potential, and the numerical value will most likely shrink as these resource values are proved-up by storage reservoir characterization prior to actual injection.

The location of CO_2 storage resource beneath Federal Lands and stationary emission sources are listed by RCSP in Table 3. The majority of leasable Federal Lands is found in PCOR Partnership and SWP, while the majority of CO_2 storage resource can be found in BSCSP and WESTCARB. However, the emissions from MRCSP and SECARB are more than double those found in the SWP, BSCSP, and WESTCARB.

Table 3. Federal Lands CO_2 Storage Potential and Stationary Sources

RCSP	Percent of Leasable Acreage	Percent of Average Storage[1]	Number of Stationary Sources[2]	Annual CO_2 Emissions[3]
BSCSP	7.5	45.8	231	160
MGSC	0.4	1.0	399	660
MRCSP	2.5	4.8	580	800
PCOR	6.6	21.9	667	500
SECARB	5.2	9.8	785	1070
SWP	20.2	8.2	362	440
WESTCARB	57.3	8.4	135	200

[1] Of High and Low estimate of CO_2 storage resource

[2] Emit >10,000 Mt/yr and within 100 miles of leasable Federal Land

[3] Million metric tons/year

The advantage of using Federal Lands for CO_2 storage field projects in the western states is the ability to assemble sufficient land from a single owner. Federal Lands east of the Mississippi occur in smaller, more disseminated blocks, and its utilization here will most likely be in conjunction with non-Federal Lands.

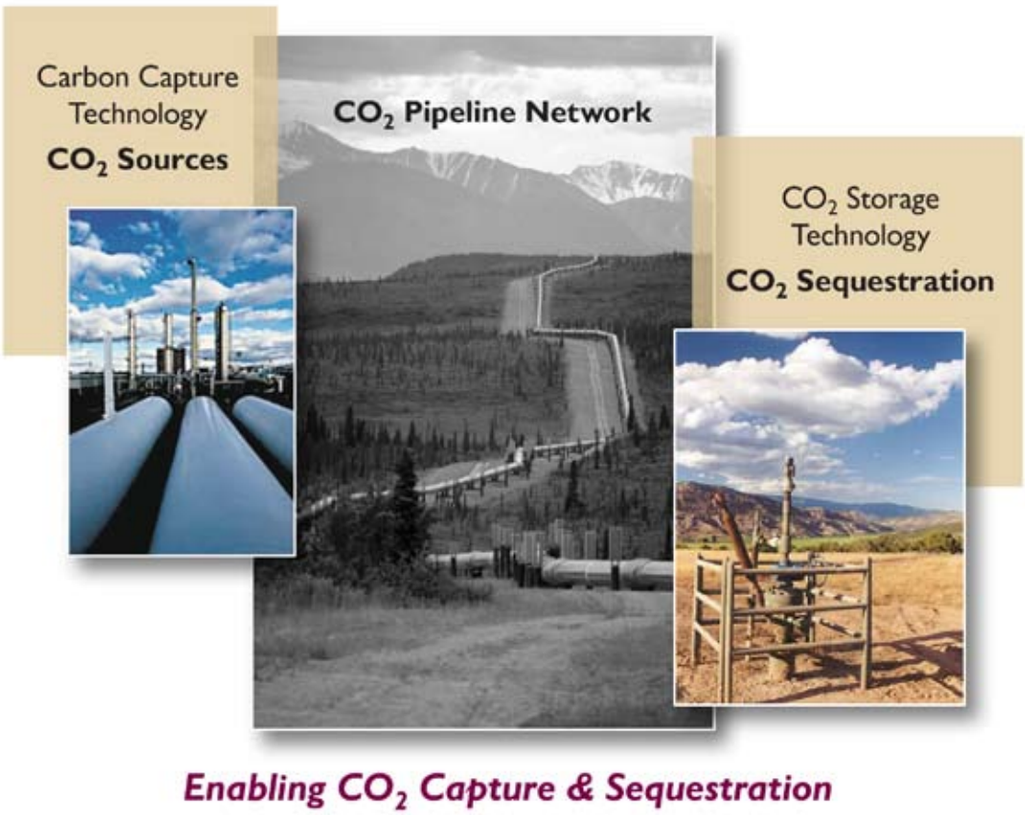
Distribution of CO_2 storage resource beneath Federal Land for oil and gas reservoirs, unmineable coal seams and saline formations is illustrated in Table 4.

Table 4. Distribution of CO_2 Storage Resource Beneath Federal Lands by Type and RCSP

Oil & Gas	Low		High	
RCSP	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	3.2	3.5	3.2	3.5
MGSC	0.0	0.0	0.0	0.0
MRCSP	2.8	3.1	2.8	3.1
PCOR	25.4	27.9	25.4	27.9
SECARB	0.5	0.6	0.5	0.6
SWP	0.0	0.0	0.0	0.0
WESTCARB	0.0	0.0	0.0	0.0
TOTAL	31.8	35.1	31.8	35.1

Unmineable Coal Seams	Low		High	
RCSP	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	0.1	0.1	0.2	0.2
MGSC	0.0	0.0	0.0	0.0
MRCSP	0.0	0.0	0.0	0.0
PCOR	1.7	1.9	1.7	1.9
SECARB	2.7	3.0	3.8	4.2
SWP	0.0	0.0	0.1	0.1
WESTCARB	0.0	0.0	0.0	0.0
TOTAL	4.5	5.0	5.8	6.4

Saline Formations	Low		High	
RCSP	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	48.2	53.0	188.0	206.8
MGSC	1.1	1.2	4.5	5.0
MRCSP	6.4	7.0	6.4	7.0
PCOR	8.2	9.0	32.8	36.1
SECARB	8.6	9.5	34.5	38.0
SWP	8.9	9.8	34.6	38.1
WESTCARB	9.1	10.0	35.9	39.5
TOTAL	90.5	99.5	336.7	370.5



CO_2 Pipeline Studies at NETL

Carbon dioxide transportation, a critical component of CCS, must be addressed in detail for successful deployment of CCS technologies. Should CCS legislation be enacted, stationary sources will be required to incorporate CO_2 capture technologies; thus a network of CO_2 pipelines will be essential for efficient and cost-effective transportation of CO_2. Linking CO_2 capture and geologic storage technologies through pipelines is a key focus of DOE's Carbon Sequestration R&D efforts.

A two-phase CO_2 Pipeline Infrastructure Study, "Developing a National CO_2 Pipeline Network," is being funded by DOE. Phase I of the study, completed in 2008, identified and analyzed the opportunities and benefits that would accrue from developing a national CO_2 pipeline network, the challenges facing such development, and the enhancement of new markets and technologies for all CCS process steps. The Phase II of the study, initiated in Spring 2008, is performing regional case studies to determine the pipeline routes that are most likely to develop to efficiently deliver CO_2 emissions from stationary sources to the nearest viable and economical geologic storage sites.

Phase I Results

If CO_2 emission reduction regulation is enacted, existing stationary sources will need to capture and sequester a portion of the 3,700 million metric tons of CO_2 emitted per year from stationary sources identified by the RCSPs. New dedicated pipelines, new codes and regulations and a new unambiguous classification of CO_2 will have to be established for safe, efficient transportation of CO_2 from these stationary sources to various geologic storage sites.

The cost of building these new pipelines will be substantial, and construction will not happen overnight. A coordinated approach backed by appropriate policy and legislation at the state and national levels will be necessary to encourage the construction of a national pipeline infrastructure. Even with uncertainties about the suitability of various geologic formations for long-term storage, the fact that major stationary sources are located close to potential geologic storage sites supports the development of a CO_2 pipeline network in stages. Without CCS, pipelines for EOR will continue to be built, but the pace of development will be market driven; with CCS, the first stage of development will likely involve building pipelines of 50 miles or less in length from stationary sources to geologic storage sites. In some situations, CO_2 may need to be transported hundreds of miles to reach a viable storage site or be delivered to a depleted oil field for enhanced oil recovery. The next stage would take pipeline development farther away from stationary sources—both intrastate and interstate.

The evolution of the pipeline network will also be impacted by the status it is ultimately accorded—whether pipelines are designated as "common carriers" (open access to all users under equal requirements) or "contract carriers" (transportation provided to shippers who enter into contracts with the pipeline operator)—and which government department has the responsibility for regulating CO_2 pipelines.

Phase II Update

The Phase II of the CO_2 pipeline study (anticipated to be completed in summer 2009), will perform regional case studies to determine the pipeline routes that are most likely to develop to efficiently deliver CO_2 emissions from stationary sources—especially from coal-fired power plants that account for the majority of emissions—to the nearest viable geologic storage sites. The implications of economics, resources, and timing of pipeline development will be evaluated. The study will also identify regional challenges and benefits to gain a better understanding of the regional differences and how these differences will affect CO_2 pipeline development. A mapped view of illustrative regional CO_2 pipeline networks will be created as a platform to determine future requirements for development of a national CO_2 pipeline network.

Statistics

- Approximately 3,700 miles of a CO_2 pipeline network were developed over 35 years.
- Approximately 320,000 miles of a natural gas transmission network and 1,215,000 miles of a natural gas distribution network were developed over 100 years.
- Approximately 123,000 tons per day of CO_2 is currently transported through pipelines.

Photo of point where CO_2 exits the underground pipeline that transports CO_2 from Beulah, ND to Weyburn, Saskatchewan (photo courtesy of PTRC and the IEA GHG Weyburn CO_2 Monitoring and Storage Project)

Anadarko CO_2 pipeline to Salt Creek

References

Bureau of Land Management, 2008, EPCA (Energy Policy and Conservation Act of 2000) Phase III Inventory, found at: http://www.blm.gov/wo/st/en/prog/energy/oil_and_gas/EPCA_III.html

Charpentier, R.R., and Klett, T.R., 2003, A Monte Carlo simulation method for the assessment of undiscovered, conventional oil and gas: U.S. Geological Survey Digital Data Series DDS-69B, 8 p., available at http://pubs.usgs.gov/dds/dds-069/dds-069-b/REPORTS/Chapter_21.pdf

Energy Information Administration, www.eia.doe.gov

Environmental Protection Agency, www.epa.gov

Ibid, Table A9-2, Federal Land Categorization, p. 372.

Klett, T.R., Schmoker, J.W., and Charpentier, R.R., 2003, U.S. Geological Survey input-data form and operational procedure for the assessment of conventional petroleum accumulations: U.S. Geological Survey Digital Data Series DDS-69B, 10 p., available at http://pubs.usgs.gov/dds/dds-069/dds-069-b/REPORTS/Chapter_20.pdf

National Atlas: Federal Lands in the United States, http://www.nationalatlas.gov/mld/fedlanp.html

National Carbon Sequestration Database and Geographic Information System (NATCARB), www.natcarb.org

National Energy Technology Laboratory, 2008, Storage of Captured Carbon Dioxide Beneath Federal Lands.

Schmoker, J.W., and Klett, T.R., 2003, U.S. Geological Survey assessment concepts for conventional petroleum accumulations: U.S. Geological Survey Digital Data Series DDS-69B, 9 p., available at http://pubs.usgs.gov/dds/dds-069/dds-069-b/REPORTS/Chapter_19.pdf

U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, Carbon Sequestration Technology Roadmap and Program Plan, 2007.

U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, Carbon Sequestration Atlas of the United States and Canada, 2007.