Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 00 (2013) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

GHGT-11

U.S. DOE's R&D Program to Develop Infrastructure for Carbon Storage: Overview of the Regional Carbon Sequestration Partnerships and other R&D Field Projects

John Litynski[1*], Traci Rodosta[1], Derek Vikara[2], and Rameshwar Srivastava[2]

[1]*National Energy Technology Laboratory,626 Cochrans Mill Road, Pittsburgh, PA 15236-0940, U.S.A.*
[2]*Keylogic Systems, Inc., National Energy Technology Laboratory, 626 Cochrans Mill Road, Pittsburgh, PA 15236-0940, U.S.A.*

Abstract

The Carbon Storage Program being implemented by the U.S. Department of Energy's (DOE) Office of Fossil Energy and managed by the National Energy Technology Laboratory (NETL) is focused on developing technologies to capture, separate, and store CO_2 in order to reduce greenhouse gas emissions without adversely affecting energy use or hindering economic growth. NETL envisions having a technology portfolio of safe, cost-effective, greenhouse gas capture, transport, and storage technologies that will be available for commercial deployment. The Carbon Storage Program involves three key technology development elements: (1) Core Research and Development (R&D), (2) Infrastructure, and (3) Global Collaborations. The integration of these elements is addressing technological and marketplace challenges.

The Infrastructure element of DOE's Carbon Storage Program is focused on R&D initiatives to advance geologic CO_2 storage commercialization. The Infrastructure element highlights DOE's awareness of the importance of addressing CO_2 mitigation on a regional level to most effectively manage differences in geology, climate, population density, infrastructure, and socioeconomic development. This element includes a series of geologic CO_2 storage field tests through the Regional Carbon Sequestration Partnership (RCSP) Initiative, as well as small-scale geologic CO_2 storage field testing efforts used to augment and build on the RCSP field test accomplishments. The Infrastructure element also includes crosscutting projects funded by the American Recovery and Reinvestment Act of 2009 (ARRA) that complement the existing Carbon Storage Program's efforts to develop carbon capture, utilization, and storage (CCUS) infrastructure in the United States. These ARRA-supported efforts include the establishment of seven CCUS training centers and nine geologic site characterization projects throughout the United States.

Carbon capture, utilization, and storage and other clean coal technologies can play a critical role in mitigating CO_2 emissions while supporting U.S. energy security. DOE's Carbon Storage Program has positioned the United States on a path toward ensuring that these enabling technologies will be available to effect broad CCUS deployment. NETL is helping to promote widespread CCUS deployment through the Carbon Storage Program's Infrastructure element, which to date has: (1) safely and efficiently injected and stored close to more than three million metric tons of CO_2 across nearly 22 active or completed field projects; (2) generated lessons learned from those field projects and

* Corresponding author. Tel.: +1-412-386-4922;
E-mail address: John.litynski@netl.doe.gov

documented them in best-practices manuals; (3) refined national CO_2 storage assessments through characterization field projects; and (4) trained nearly 3,000 students through the Regional Carbon Sequestration Training Centers. Even though NETL's Carbon Storage R&D Program is being implemented through several different initiatives, it should be viewed as an integrated whole, with many of the goals and objectives transitioning from one initiative to the next.

Keywords: DOE, NETL, Regional Carbon Sequestration Partnerships, CCUS Infrastructure, ARRA Site Characterization, ARRA Regional Carbon Sequestration Training

---

Overview

Fossil fuels are considered the most dependable, cost-effective energy source in the world. The availability of these fuels to provide clean, affordable energy is essential for future U.S. and global prosperity and security. However, a balance must be made between energy security and increasing concerns over the impacts due to increasing concentrations of greenhouse gases (GHGs) in the atmosphere—particularly carbon dioxide (CO_2) [1]. A combined portfolio of carbon management options can be employed to manage current GHG emission levels while promoting energy security and developing the technologies and knowledge base for export to other countries challenged with reducing emissions.

The U.S. Department of Energy (DOE) launched its Carbon Storage (formally Sequestration) Program in 1997 with a goal of developing and advancing carbon capture, utilization, and storage (CCUS) technologies with significant potential to reduce GHG emissions that will be ready for widespread commercial deployment by 2030. Since 1997, DOE's Carbon Storage Program has significantly advanced the CCUS knowledge base in selected technology areas through a diverse portfolio of applied research projects. The Carbon Storage Program comprises three principal elements: Core Research and Development (R&D), Infrastructure, and Global Collaborations. It is the integration of these elements that will address technological and marketplace challenges. The Infrastructure element of DOE's Carbon Storage Program is focused on R&D initiatives to advance geologic CO_2 storage toward commercialization [2]. The Infrastructure element highlights DOE's awareness of the importance of addressing CO_2 mitigation on a regional level to most effectively account for differences in geology, climate, population density, infrastructure, and socioeconomic development. This element supports the development of regional infrastructure for CCUS throughout the United States through several efforts, including a series of geologic CO_2 storage field tests through the Regional Carbon Sequestration Partnership (RCSP) Initiative, as well as small-scale geologic CO_2 storage field testing efforts used to augment and build on the RCSP field test accomplishments. The Infrastructure element also includes crosscutting projects funded by the American Recovery and Reinvestment Act of 2009 (ARRA) that complement the existing Carbon Storage Program's efforts to develop CCUS infrastructure in the United States. These ARRA-supported efforts include the establishment of seven CCUS training centers to promote knowledge-sharing and lessons learned from field projects, and nine geologic site characterization projects to enhance and better understand the nation's CO_2 geologic storage capacity. These infrastructure efforts are highlighted below:

- **Regional Carbon Sequestration Partnerships (RCSPs):** Seven RCSPs are tasked with determining the best geologic and terrestrial storage approaches and applying technologies to safely and permanently store CO_2 in specific regions throughout North America. The RCSPs are public/private partnerships comprised of more than 400 organizations in 43 states and four Canadian provinces. They 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. This RCSP Initiative established the basic structure and initial findings for CCUS resources throughout the United States and portions of Canada that are being further enhanced by additional small- and large-scale CO_2 injection projects designed to address specific applied research related to advancing both geologic and terrestrial storage. In addition, the RCSPs began studying possible regulations and infrastructure requirements that would be needed should CCUS be deployed on a commercial basis.

- **Small-Scale Field Tests:** NETL is supporting four CO_2 injection tests in geologic formations and depositional environments dissimilar to those investigated through the RCSP or ARRA Site Characterization efforts, in order to understand CO_2 behavior and migration throughout a full spectrum of depositional environments/classes of storage formations. These small-scale tests generally involve relatively modest (<500,000 metric tons CO_2) injection volumes and are aimed specifically at increased understanding CO_2 injectivity, storage capacity, and CO_2 storage in various geologic systems.

- **ARRA Geologic Site Characterization Efforts:** NETL is promoting a significant effort to characterize storage formations and reduce uncertainty associated with capacity resource estimates in North America. NETL selected nine projects to characterize promising geologic formations for CO_2 storage. These projects focus on the regional site characterization of “high-potential” geologic storage formations that include saline formations, depleting/depleted oil fields, and unmineable coal seams with the goal of developing comprehensive data sets of formation characteristics, while also gathering information and gaining experience to refine best practices for storage site selection and characterization.

- **ARRA Regional Carbon Sequestration Training Centers:** Distribution of the results and lessons learned from both field projects and Core R&D efforts will provide the foundation for future large-scale CCUS field tests across North America and address challenges associated with their public acceptance, infrastructure, and regulatory framework. Implementing CCUS technologies will require a significantly expanded workforce trained in various specialties that are currently underrepresented in the United States. NETL is supporting seven ARRA-funded Regional Carbon Sequestration Training Centers that are developing professional training classes and academic curricula for scientists, engineers, lawyers, business professionals, and others involved in CCUS project development.

Even though NETL’s Carbon Storage Infrastructure element is being implemented through several different initiatives, it should ultimately be viewed as an integrated whole, with many of the goals and objectives transitioning from one initiative to the next. In particular, the initiatives under the Infrastructure element have been successful at supporting the development of regional infrastructure for CCUS throughout the United States through (1) refining national efforts to identify stationary CO_2 sources, characterize potential storage formations, and reduce uncertainty associated with capacity resource estimates; (2) develop small- and large-scale CO_2 injection tests in different classes of geologic formations; and (3) support the development of human capital, stakeholder networking, regulatory policy development, carbon mitigation plans, and public outreach and education throughout the United States [1].

Regional Characterization Efforts

The process of identifying suitable geologic storage sites with adequate storage potential involves methodical and careful analysis of the features of promising geologic formations. While geologic formations are infinitely variable in detail, they are classified by geologists and engineers by their trapping mechanism, hydrodynamic conditions, lithology and, more recently, by their depositional environment [3]. NETL has determined that deploying CCUS on a commercial scale will require (1) optimizing CO_2 source to sink matching; (2) geologic storage formations capable of storing large volumes of CO_2; (3) injection of CO_2 at an efficient and economic rate; and (4) safely retaining CO_2 over extended periods. The efforts of the RCSPs, other large- and small-scale CO_2 injection projects, the ARRA Site Characterization projects, and the National Carbon Sequestration Database and Geographic Information System (NATCARB) have substantially increased our understanding of the potential to use geologic formations not previously studied in detail for use in geologic storage of CO_2.

Since its inception in 2003, NETL's RCSP Initiative has continued to characterize and refine geologic and terrestrial opportunities for carbon storage and identify CO_2 stationary sources within each RCSP's respective study region [2]. Data gathered by the RCSPs and NATCARB show that CO_2 stationary source emissions result largely from power generation, and industrial processes (Figure 1). While not all potential GHG sources have been examined, NETL has documented the location of 4,285 major CO_2 stationary sources throughout the United States and Canada with total annual emissions of approximately 3.347 billion metric tons of CO_2 [2].

As large power plants begin to capture CO_2, suitable storage formations and storage projects will be needed to accommodate larger volumes of captured CO_2 [2]. NETL has primarily focused geologic storage R&D on three underground storage types, saline formations, oil and gas reservoirs, and unmineable coal seams, each with unique challenges and opportunities. However, organic-rich shales and basalt formations are promising geologic storage types NETL is also investigating through characterization efforts (Appendix A). All these storage types are widely distributed throughout North America (Figure 1) and have the potential to hold total CO_2 emissions from large point sources into the distant future.

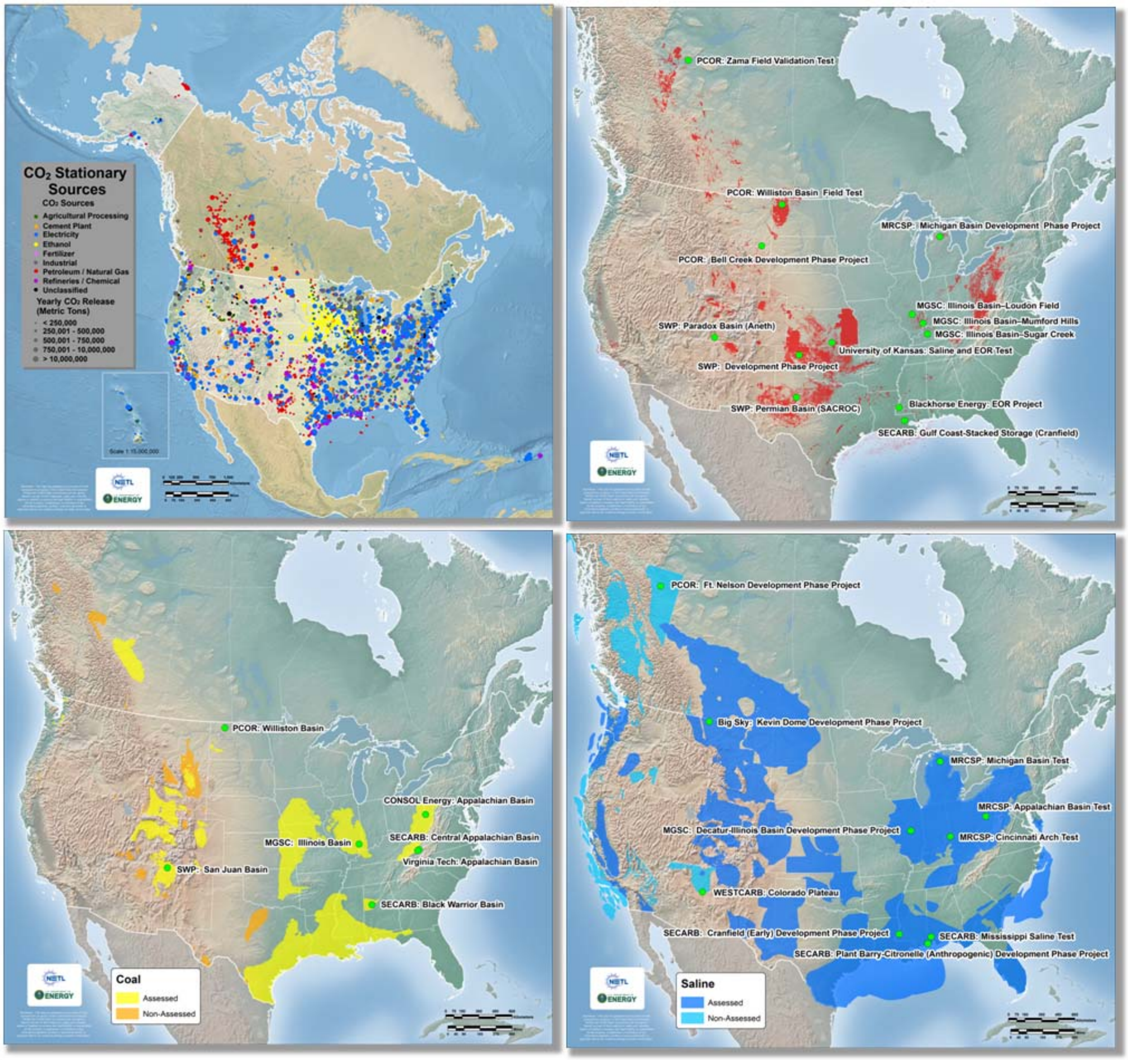


Figure 1. Distribution of CO_2 point sources (top left), oil and gas reservoirs (top right), saline-bearing formations (bottom right), and unmineable coal seams (bottom left) throughout the RCSP Regions [2]. NETL's Carbon Storage Infrastructure field projects locations are plotted based on storage formation type. Not visible in Figure 1 is the storage resources for Hawaii and Alaska. The maps were zoomed to best show field project locations.

The largest potential storage resource for geologic storage is in saline formations, and it is this potential that drives interest in CCUS to be a significant carbon management option. Saline formations being evaluated are porous sedimentary deposits saturated with brine that have salinity greater than 10,000 mg/l total dissolved solids (TDS) and they are widely distributed globally. However, in the near term, mature oil and natural gas fields provide a financially attractive option as sites for storage because of the comparative wealth of information and existing data regarding site-specific subsurface geology, existing infrastructure, and economic incentive in the form of enhanced recovery of oil (EOR) or natural gas (EGR), which will help reduce the costs of capture, transportation, injection, and monitoring. As CCUS matures, higher cost of oil, increased availability of CO_2, and available CO_2 storage resource in oil and gas formations are reasons that the EOR industry could provide a mechanism for utilizing and storing significantly more CO_2 than it does under current conditions. Mature or abandoned natural gas fields could provide large advantages for early storage projects [5]. Similarity, injection of CO_2 into coal seams can be advantageous due to storage potential (both domestically and globally) and the additional benefit at some sites of enhanced coalbed methane production (ECBM). CO_2 injection into coal seams (either as a gas or a supercritical fluid) results in sorption of CO_2 on organic-rich surfaces within the coal and, depending on the hydrostatic pressure, methane being liberated and produced while the CO_2 is retained. However, geologic storage in unmineable coal seams through adsorption processes is still a relatively immature geologic storage type and needs additional research because of the technical risks associated with swelling of the solid coal matrix during the adsorption process, resulting in reduced cleat aperture and overall permeability [6].

The potential resource for CO_2 storage in oil and gas formations, saline formations, and unmineable coals seams in North America is significant, representing at least several hundred years of emissions from large stationary sources (currently >3.347 billion metric tons emitted annually for major stationary sources across parts of Canada and the U.S.). Table 1 provides a summary of assessed CO_2 storage potential across parts of Canada and the U.S.

Table 1. CO_2 Storage Resource Estimates for Promising Geologic Storage Formations across Regional Partnership Regions [2]

Regional Partnership	Oil and Gas Formation (billion metric tons)	Saline Formations (billion metric tons)	Unmineable Coal Seams (billion metric tons)
Big Sky	0.8	98.5 – 1,237	0.58 – 1.08
MGSC	0.1 – 0.4	11.5 – 157.8	1.61 – 3.17
MRCSP	48.1	95.1 – 123.2	0.83
PCOR	25.6	86.4 – 288.8	13.79
SECARB	32.3	1,438.1 – 15,075.8	32.71 – 74.94
SWP	139.6	266.2 – 2,800.7	0.68 – 1.63
WESTCARB	3.6 – 6.7	81.7 – 1,123.9	10.92 – 24.96
Total	250.1 – 253.5	2,077.4 – 20,807.4	61.12 – 120.41

NETL continues to further advance a national assessment of CO_2 storage resources in deep geologic formations through nine field projects, funded primarily through the ARRA. These ARRA geologic characterization projects are characterizing additional promising geologic formations for CO_2 storage and are providing greater insight into the potential for geologic reservoirs across the U.S. to safely and permanently store CO_2 (Figure 2 and Table 2). The formations selected for characterization are validating confining zone (seal) properties to protect against adverse impacts on the overlying formations or risks to underground sources of drinking water (USDWs). As of April 2012, these nine projects have identified a total of over 50 billion metric tons of additional CO_2 storage potential within their respective study areas.

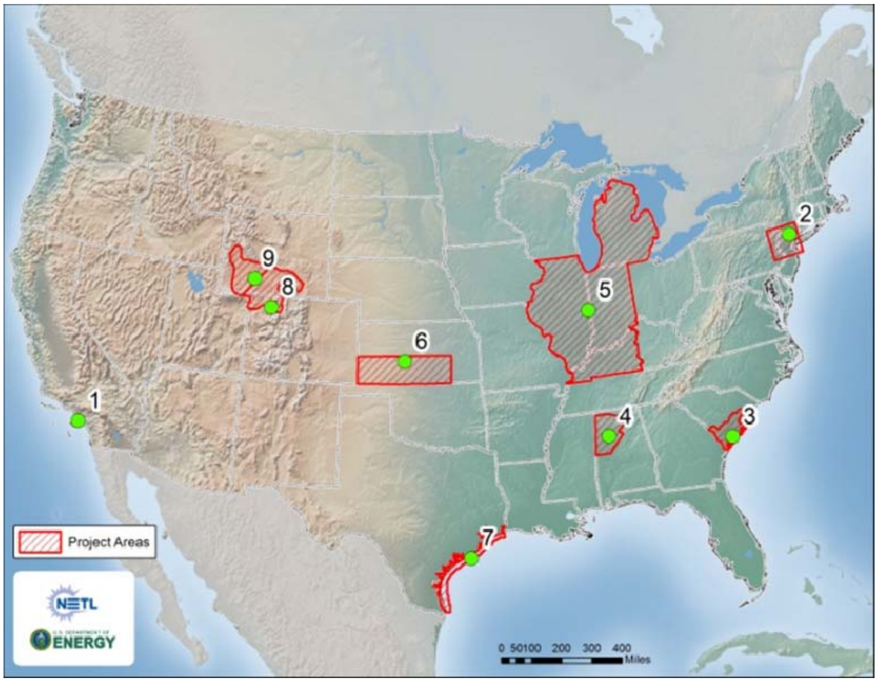


Figure 2. Project locations and study areas for the nine ARRA Site Characterization Projects. Location numbers are referenced to Table 2.

Table 2: Project-specific details, such as performer name, project title, and geologic formations under investigation, for the nine ARRA Site Characterization projects.

Key	Participant	Project Title	Characterization Activities
1	**GeoMechanics Technology**	Characterization of the Pliocene and Miocene Formations in the Wilmington Graben, Offshore Los Angeles, for Large Scale Geologic Storage of CO_2	Offshore 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	Mississippian-age Hartselle and Tuscumbia formations, Ordovician-age Stones River and Knox formations, Black Warrior Basin
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 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

The projects are developing comprehensive data sets of formation characteristics (porosity, permeability, reservoir architecture, cap rock integrity, etc.) while also developing information and experience to refine best practices for storage site selection and characterization. Projects are further refining storage resource estimates through utilizing existing data sets, drilling new characterization wells, collecting cores, running logs, conducting seismic surveys, and developing regional site geologic models based on field results. These efforts represent a significant step toward understanding the geology of potential storage formations in the United States. These projects are contributing to the knowledge base for site characterization and support further updates to best practices manuals (BPMs) for site characterization of their region. In addition, they will contribute to "knowledge sharing" within technical working groups. Specific details about these projects can be found on NETL's Carbon Storage Website [7].

Geologic Storage Field Projects

Carbon dioxide injection tests in different types of geologic formations and depositional environments that include the efforts of the RCSPs and other NETL-supported small-scale field projects are focused on contributing to the understanding of CO_2 behavior and migration in the full range of depositional environments/classes of storage formations. These tests are also aimed specifically at understanding CO_2 injectivity; validating CO_2 storage resource potential through both regional and project-specific characterization efforts; ensuring that CO_2 can be injected and stored safely, permanently, and economically; as well as validating and field testing CCUS technologies through all stages leading to commercialization [8]. NETL's Carbon Storage Program has supported a total 31 field geologic CO_2 storage projects through its Infrastructure element (project locations found on the maps in Figure 1 – the Big Sky Validation field test investigating basalts as CO_2 storage options is not listed).

Small-Scale Field Projects

A portion of the Infrastructure element is made up of a total of 22 small-scale field projects. The RCSPs have conducted the majority of these field tests through their Validation Phase (2005–2011). The Validation Phase evaluates promising CCUS projects through a series of small-scale field tests to develop an understanding of injectivity, capacity, and storability of CO_2 in the various geologic formations within a wide-range of depositional environments. Experience gained and lessons learned from this phase are being utilized to (1) develop "best practices" manuals, (2) facilitate future CCUS opportunities world-wide, and (3) provide a foundation for implementation of the large-scale field tests in the Development Phase [6]. The Validation Phase has accounted for 18 total field projects. To date, eight RCSP Validation Phase projects have completed CO_2 injection into depleted oil and gas fields; five projects have completed injection into saline formations; and five projects have completed injection into unmineable coal seams. Results from these and other field tests are presented in Table 3. These 18 Validation Phase projects have safely injected approximately 1.22 million metric tons of CO_2. The RCSPs have determined that a majority of the injected CO_2 across all of the Validation Phase projects is considered stored within the subsurface. Sophisticated monitoring, verification, and accounting (MVA) protocols were specifically designed and deployed at each project site to verify CO_2 storage within the injection zone in the subsurface. MVA protocols used at saline injection tests indicated no signs of CO_2 leakage from the injection zone in the subsurface, providing evidence of safe and permanent storage. Instrumentation, such as flow meters, were deployed at test sites to track CO_2 injected underground and to account for CO_2 (typically through mass balance) recovered from production wells, separated, and re-injected as part of the larger EOR field projects. Instrumentation was used to account for losses that occurred during the production step for some of the smaller ECBM and EOR projects not utilizing recycle. Ensuring storage for all new CO_2 received at a project site requires CO_2 tracking at all operational stages, including CO_2 received, injected, reproduced, and recycled. NETL's small-scale field tests have utilized detailed CO_2 tracking at each project stage, which is critical in optimizing CO_2 storage efforts within existing EOR operations. Results and lessons learned from the Validation Phase Projects have provided a basis and a foundation for which the RCSP large-scale Development Phase field tests and other large-scale CO_2 projects can be designed and implemented. Specific details about each RCSP test can be found on NETL's Carbon Storage Regional Partnership Website [9].

Table 3. Summary of NETL's Carbon Storage Infrastructure Small-scale Field Projects

Oil and Gas Formation Tests				
Test	Injected Volume (CO_2)	Storage Formation (Thickness)	Depositional Environment	CO_2-EOR Activity
MGSC: Illinois Basin–Loudon Field	39 metric tons	Missippian Weiler Sandstone (16 feet)	Delta Tidal Dominated (Clastic)	93 bbl produced
MGSC: Illinois Basin–Sugar Creek	6,560 metric tons	Jackson Sandstone (5–20 feet)	Marine Shelf (Clastics)	2–3 times increase in current production rate
MGSC: Illinois Basin–Mumford Hills	6,300 metric tons	Clore Formation (10–40 feet)	Fluvial Channel (Clastic)	4–8 times increase in current production rate
PCOR: Williston Basin Field Test	400 metric tons	Mission Canyon Formation (14 feet)	Shallow Shelf (Carbonate)	~240 bbl produced
PCOR: Zama Field Validation Test	84,986 metric tons	Keg River Formation (35-40 feet)	Pinnacle Reef (Carbonate)	74,200 bbl produced
SECARB: Gulf Coast-Stacked Storage (Cranfield)	627,744 metric tons	Tuscaloosa Formation (90 feet)	Fluvial (Clastic)	NA
SWP: Permian Basin (SACROC)	157,000 metric tons	Cisco-Canyon (213 feet)	Reef (Carbonate)	Increase from 575 to 2,000 bbl/day
SWP: Paradox Basin (Aneth)	254,000 metric tons	Desert Creek and Ismay (200 feet total)	Shallow Shelf Restricted (Carbonate)	~159,000 bbl produced
Blackhorse Energy: EOR Project	52,000 metric tons (Anticipated)	First Wilcox Sand (50 feet)	Shallow Shelf (Clastic)	NA
University of Kansas: Saline and EOR Test	30,000 metric tons (Anticipated)	Mississippian Formation (up to 50 feet)	Open Marine Shelf (Carbonate)	NA

Saline Formation Tests				
Test	Injected Volume (CO_2)	Storage Formation (Thickness)	Depositional Environment	Confining System (Thickness)
MRCSP: Michigan Basin Test	60,000 metric tons	Bass Island Dolomites (73 feet)	Shallow Shelf (Carbonate)	Amherstburg (2,000 feet)
MRCSP: Cincinnati Arch Test	910 metric tons	Mt. Simon Sandstone (300 feet)	Strandplain (Clastic)	Eau Claire Shale (400 feet)
MRCSP: Appalachian Basin Test	<50 metric tons	Oriskany (30 feet) Salina (200 feet) Clinton (70 feet)	Shallow Shelf (Clastic)	Chagrin Shale (1,000 feet) Lower Huron Shale (1,400 feet) Rhinestreet Shale (700 feet)
SECARB: Mississippi Saline Test	,2,711,600 metric tons	Lower Tuscaloosa (120 feet)	Delta Marine (Clastic)	Marine Tuscaloosa (500 feet) Midway Shale (350 feet) Selma Chalk/Austin (1,300 feet)
WESTCARB: Colorado Plateau	Insufficient permeability for injection	Naco/Martin Formations (700 feet)	Shallow Shelf (Carbonate)	Supal Formation (1,900 feet)
Unmineable Coal Seam Field Tests				
Test	Injected Volume (CO_2)	Storage Formation (Thickness)	Avg. Adsorption (scf/ton)	Results
MGSC: Illinois Basin	91 metric tons	Springfield Coal (7 feet)	1,075 @ 390 psi	Injection decreased then stabilized
PCOR: Williston Basin	80 metric tons	Fort Union Coals (10 feet)	350 @ 350 psi	Increased injection rate by heating CO_2
SECARB: Black Warrior Basin	252 metric tons	Black Creek, Mary Lee, and Pratt (1–6 feet each)	600–900 @ 350psi	Higher than expected injectivity
SECARB: Central Appalachian Basin	914 metric tons	Pocahontas & Lee (36 feet)	300–750 @ 350 psi	Injectivity decreased to 20 metric tons per day
SWP: San Juan Basin	16,700 metric tons	Fruitland Coal Seams (60 feet)	809 @ 317 psi 776 @ 269 psi 1,038 @ 372 psi	Lower injection rate than anticipated
CONSOL Energy: Appalachian Basin	2,430 metric tons	Upper Freeport and Pittsburgh Coal Seams (1–10 feet each)	1,378 @ 920 psi[10]	Injection rate, gas recovery as expected.
Virginia Tech: Appalachian Basin	20,000 metric tons anticipated	Horsepen, Pocahontas, and Sewell Seams (10–26 feet total)	Injection not initiated	Injection not initiated

Other small-scale projects supported by NETL augment what has been learned to date from the 18 small-scale field tests conducted by RCSPs during the Validation Phase. While the RCSP tests have provided valuable data, gaps remain in the understanding of the complex issues surrounding the processes associated with geologic CO_2 monitoring and storage across various types of formations and depositional environments. NETL has awarded Blackhorse Energy, LLC and the University of Kansas funding to conduct small-scale testing in oil and gas formations (Table 3).

Blackhorse Energy, LLC plans to inject supercritical CO_2 into a beach barrier bar complex in southeastern Louisiana to evaluate the formation for long-term CO_2 storage potential and supplement existing enhanced oil recovery (EOR) activities. The primary focus of this project is to examine and prove the suitability of South Louisiana geologic formations for geologic storage of CO_2 in association with EOR applications. The project is using an innovative injection well design to test the efficacy of increased geologic storage in the Wilcox Formation. Short-radius horizontal well technology will be used to inject approximately 52,000 metric tons of supercritical CO_2 and CO_2 foam into the Wilcox Formation. The project also will use innovative remote time-lapse monitoring technologies to track CO_2 migration during and after injection operations.

The University of Kansas project aims to inject at least 30,000 metric tons of CO_2 into the Mississippian formation and 40,000 metric tons under super-critical conditions into the underlying Arbuckle saline aquifer to evaluate geologic storage of CO_2 and miscible CO_2-EOR. This study will apply state-of-the-art MVA tools and techniques to monitor and visualize the injected CO_2 plume and develop a robust Arbuckle geomodel by integrating data collected from the proposed study area. The team will integrate MVA data and analyses with reservoir modelling studies to detect potential CO_2 leakage and validate the simulation model.

The CONSOL Energy project has utilized horizontal drilling on a 200-acre site with two underlying coal seams to produce coalbed methane (CBM) and store CO_2 in unmineable coal formations. CONSOL has constructed and operated a coal bed CO_2 storage site composed of a series of wells that originate at the surface and extend horizontally through two overlying coal seams. The wells were initially to drain CBM from both the upper (mineable) and lower (unmineable) coal seams. After sufficient depletion of the reservoir, centrally located wells in the lower coal seam were converted from CBM drainage wells to CO_2 injection wells. The CONSOL Energy project is currently injecting 6 metric tons per day for a total of ~2400 metric tons as of early September.

NETL continues advanced research into CO_2 behavior in coal seams by partnering with Virginia Polytechnic and State University (Virginia Tech) for a new field test. Limited experience with injection into coal and organic-rich shales in central Appalachia makes commercial potential uncertain at this time. Working in partnership with NETL, the Virginia Tech project is focused on reducing this uncertainty by designing and implementing characterization, injection, and monitoring activities to test these stacked formations (listed in Table 3) and track the migration of CO_2 throughout the injection and post-injection phases. A detailed geologic characterization of the proposed injection site indicates that regional geologic structures, coal permeability, and reservoir seals are adequate for a 20,000 metric ton injection test. The proposed research will provide needed information on other stacked storage options and provide an additional benefit of proven carbon storage potential in coal seams with ECBM and other stacked unconventional formations in central Appalachia. Many of the CBM operations in the central Appalachian Basin are approaching maturity, providing large reservoirs suitable for storing CO_2. Carbon dioxide injection into coal seams could increase CBM reserves by 20 to 40 percent while concurrently increasing the storage capacity for sequestration of large volumes of CO_2.

Large-scale Field Projects

DOE is supporting a number of large-scale (1 million metric tons CO_2 injected) field projects in different geologic storage formations to confirm that CO_2 capture, transportation, injection, and storage can be achieved safely, permanently, and economically at commercial-scale. The large-scale field projects are exclusive to the RCSP Development Phase (2008–2018+) and involve at least one injection of approximately one million metric tons or more of CO_2 by different RCSPs into regionally significant geologic formations of different depositional environments, focusing on saline formations and EOR injections (Table 4). The results of the characterization and injection processes of these projects should provide enough information to refine the regional storage resource estimates to a more specific storage resource estimate for the project site and to classify each site as "Contingent Storage Resource" [3][6]. Regional variations among RCSP projects will provide researchers with vitally important information and experience as they (1) test injection across a variety of geologic settings, (2) engage stakeholders and the public to provide education and insight into CCUS activities, and (3) contribute to the development of permitting and other regulatory requirements that will be used for long-term injection and geologic storage of CO_2. These projects are considered the precursors to commercial-scale major demonstration projects.

In addition to the various depositional environments being tested, the RCSP Initiative's Development Phase projects are also exploring issues concerned with using CO_2 from a variety of CO_2 sources including naturally occurring deposits, ethanol facilities, natural gas processing plants, and capture from power plants [2]. Using CO_2 from a variety of sources across Partnership tests provides insight into the required infrastructure, costs, and overall level of effort needed to capture and safely store CO_2 from a particular source type. Tests are designed to not only investigate commercial-scale injection of CO_2, but also to understand the necessary regulatory and public outreach efforts needed for successful CCUS, and to develop the necessary human capital, knowledge base, and experience necessary to implement future CCUS operations.

Table 4: Summary of NETL's Carbon Storage Infrastructure Large-Scale Field Projects

Test	Expected Injected Volume (CO_2)	Storage Formation (Thickness)	Depositional Environment	Project Type
Big Sky: Kevin Dome Development Phase Project	1,000,000 metric tons total	Duperow Formation (up to 750 feet)	Shallow Shelf (Carbonate)	Saline Storage
MGSC: Decatur-Illinois Basin Development Phase Project	1,000,000 metric tons total	Mt. Simon Sandstone (>1,600 feet)	Fluvial/Deltaic (Clastic)	Saline Storage
MRCSP: Michigan Basin Development Phase Project	1,000,000 metric tons total	Northern Fairway of Niagaran Reef Complex (Depth at site TBD)	Pinnacle Reef (Carbonate)	EOR
PCOR: Bell Creek Development Phase Project	>1,000,000 metric tons total	Muddy Formation (35-40 feet)	Fluvial Deltaic (Clastic)	EOR
PCOR: Ft. Nelson Development Phase Project	>1,000,000 metric tons total	Elk Point Group (Depth at site TBD)	Reef (Carbonate)	Saline Storage
SECARB: Plant Barry-Citronelle (Anthropogenic) Development Phase Project	up to 300,000 metric tons total	Paluxy Formation (1,150 feet)	Fluvial Deltaic and Shallow Marine (Clastic)	Saline Storage
SECARB: Cranfield (Early) Development Phase Project	>2,000,000 metric tons total	Lower Tuscaloosa Formation (475 feet)	Fluvial Deltaic and Shallow Marine (Clastic)	Saline Storage
SWP: Development Phase Project	>1,000,000 metric tons total	Morrow Formation (~7,700 feet)	Fluvial Deltaic (Clastic)	EOR

Eight tests are slated for the Development Phase; seven project sites have already been selected and the remaining site is finalizing negotiations (Table 4). The majority of projects that have selected sites are currently undergoing site characterization and preparation, project planning, and permitting activities. However, injection operations have begun at the Midwest Geologic Sequestration Consortium (MGSC) Decatur-Illinois Basin site, and at the Southeast Regional Carbon Sequestration Consortium (SECARB) Cranfield (Early) and Plant Barry-Citronelle (Anthropogenic) sites.

The MGSC Decatur-Illinois Basin project involves the injection of 1 million metric tons of CO_2 over three years into a deep saline formation in the Illinois Basin. The source of CO_2 is downstream of the product recovery scrubbers that follow the Archer Daniels Midland (ADM) ethanol fermentation units. Since November 2011, CO_2 has been injected and stored at a rate of over 1,000 metric tons per day. MVA activities are focused on the 0.65 km^2 project site and critical locations in the surrounding area. A major objective of monitoring is to establish an environmental baseline to allow evaluation of potential impacts from CO_2 injection, to demonstrate that project activities are not adversely affecting human health and the environment, and provide an accurate accounting of stored CO_2. The effectiveness of long-term CO_2 storage in the Mt. Simon is being evaluated through an in-zone verification well designed to monitor the injection formation and formations immediately above the primary caprock using pressure monitoring and fluid sampling. A dedicated geophone well has been drilled to facilitate repeat seismic imaging over the life of the project. Surface deformation will be measured using interferometric synthetic aperture radar (InSAR) satellite imagery. Monitoring of the near-surface environment includes color infrared aerial imagery, high-resolution electrical earth resistivity, shallow groundwater quality, soil CO_2 fluxes, net exchange CO_2 fluxes, and vadose zone CO_2 concentrations. Characterization of near-surface CO_2 conditions is important to determine baseline conditions for detecting any potential CO_2 leakage to the atmosphere.

The SECARB Cranfield (Early) site, which was the first Development Phase field test to begin CO_2 injection operations, injects CO_2 into the lower Tuscaloosa Formation. The Cranfield project began injection in April 2009 after a successful Validation Phase test that injected and stored over 627,000 metric tons of CO_2 into the Tuscaloosa and the same site. An additional 2,711,600 metric tons of CO_2 has been injected through the end of 2011. The naturally occurring CO_2 for the Cranfield project is sourced via CO_2 pipeline from the Jackson Dome near Jackson, Mississippi. In August 2012 the Plant Barry-Citronelle (Anthropogenic) project has begun injecting at a rate of 100,000 to 150,000 metric tons of CO_2 per year for two to three years into the Paluxy Formation. The CO_2 is being supplied by a pilot unit capturing CO_2 from flue gas produced from Southern Company's coal fired facility, Plant Barry in Bucks, Alabama and transported 12 miles by pipeline to the Citronelle Field injection site. Three new wells have been drilled for the project—a reservoir characterization well, a characterization/observation/backup injection well, and a dedicated CO_2 injection well. In addition to the new wells, the project is using several existing oilfield wells surrounding the CO_2 injection site to monitor injection operations and to ensure public safety. Mitsubishi Heavy Industries successfully completed construction of a post-combustion CO_2 capture facility at Plant Barry that became operational in the Summery of 2011.

Specific details about each RCSP test can be found on NETL's Carbon Storage Regional Partnership website [9] or in the 2012 United States Carbon Utilization and Storage Atlas (Atlas IV) [2].

Regional Carbon Sequestration Training Centers and Knowledge Sharing

DOE understands that knowledge sharing between various entities is essential in order to commercialize CO_2 storage technologies. Distribution of the results and lessons learned from both field projects and Core R&D efforts will provide the foundation for future, large-scale CCUS field tests across North America and for addressing future challenges associated with public acceptance, infrastructure requirements (pipelines, compressor stations, etc.), and regulatory framework. DOE promotes information and knowledge sharing through various avenues, such as the RCSP working groups, development of best-practices manuals [11], public outreach and education efforts including the NETL Carbon Storage Program website, and through ARRA Regional Carbon Sequestration Training Centers (Training Centers) [12].

The seven training centers established by NETL are focused on training personnel in the implementation of CCUS technology (Table 5). While CCUS technologies offer great potential for reducing CO_2 emissions and mitigating potential climate change, deploying these technologies will require a significantly expanded workforce trained in various specialties that are currently underrepresented in the United States. The training activities focus on the applied engineering and science of CCUS for site developers, geologists, engineers, and technicians, as well as provide a technology transfer platform for

CO_2 storage. The resulting training will produce a workforce with the skills and competencies in geology, geophysics, geomechanics, geochemistry, and reservoir engineering disciplines needed by the CCUS industry. The goal of these training centers is to become self sustaining (without Federal funding) while continuing training to ensure a technically capable CCUS workforce when CCUS is commercially deployed. The seven centers are augmenting and supplementing outreach activities already underway in RCSPs, and are utilizing the experiences and lessons learned from NETL's Core R&D efforts, CO_2 storage field projects, and characterization efforts as key components for training curricula [12]. The seven training centers are listed in Table 5, with links to their respective websites for more information.

Table 5. NETL's ARRA Regional Carbon Sequestration Training Centers

Performer	Training Center	Location	Website
University of Illinois	Midwest Geological Sequestration Consortium Sequestration Training and Education Program (STEP)	Champaign, Illinois	http://www.sequestration.org/step/
Environmental Outreach and Stewardship (EOS) Alliance	Carbon Capture and Storage Training	Seattle, Washington	https://nwetc.org/index.php
New Mexico Institute of Mining and Technology	Southwestern United States Carbon Sequestration Training Center	Socorro, NM	http://www.ccstrend.org/
Petroleum Technology Transfer Council	Carbon Capture and Storage in the Permian Basin, a Regional Technology Transfer and Training Program	Tulsa, Oklahoma	http://www.pttc.org/
Southern States Energy Board (SSEB)	Carbon Capture and Storage in the Permian Basin, a Regional Technology Transfer and Training Program	Norcross, Georgia	http://www.secarb-ed.org/
University of Texas at Austin	Alliance for Sequestration Training, Outreach, Research and Education (STORE)	Austin, Texas	http://www.storeco2now.com/
University of Wyoming	Wyoming Carbon Capture and Sequestration Technology Institute; Workforce Training, Technology Transfer, and Information Clearinghouse	Laramie, Wyoming	http://www.wyomingcarbonstorage.com/

As of June 2012, a total of 5,523 Professional Development Hours (PDHs) and 1,129 Continuing Education Units (CEUs) have been obtained, and approximately 2,941students have participated in CCUS training provided by the seven training centers. Specific details about each training center can be found on NETL's Carbon Storage ARRA Regional Carbon Sequestration Training Center website [12].

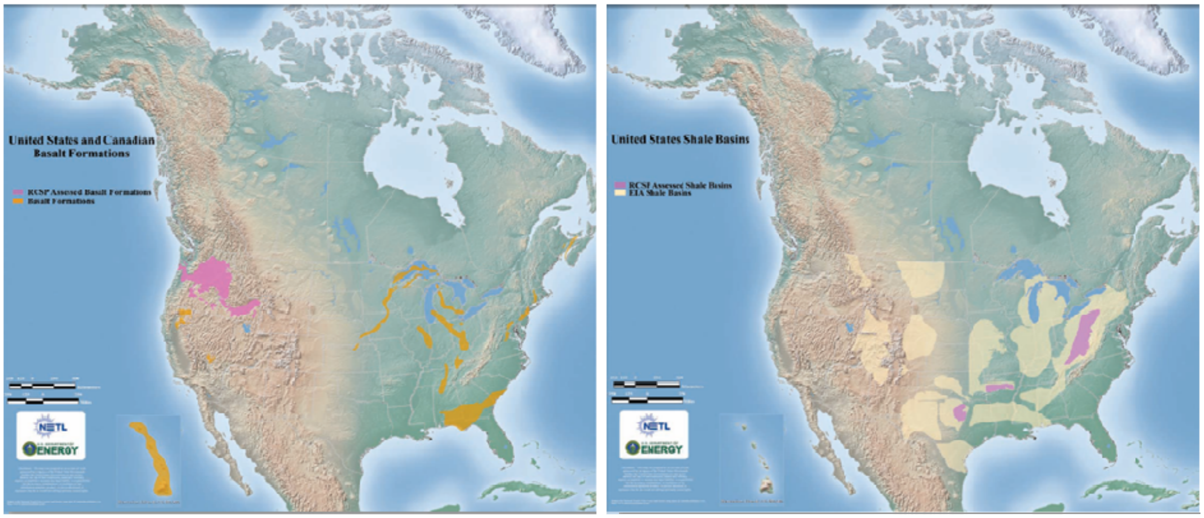
Conclusions

Carbon capture, utilization, and storage and other clean coal technologies could play a critical role in mitigating CO_2 emissions while supporting U.S. energy security. DOE's Carbon Storage Program has positioned the United States on a path toward ensuring that these enabling technologies will be available to effect broad CCUS deployment. Addressing CO_2 mitigation from a regional perspective is an effective way to address differences in geology, climate, population density, infrastructure (human capital), and socioeconomic development throughout the United States. NETL is supporting the development of regional infrastructure for CCUS throughout the United States through the Carbon Storage Program's

Infrastructure element, which is focused on R&D initiatives to advance geologic CO_2 storage toward commercialization.

NETL is helping to promote widespread CCUS deployment through the Infrastructure element, which to date has safely and efficiently injected and stored more than three million metric tons of CO_2 at over 20 active or completed field projects; generated lessons-learned from those field projects and documented them in best-practices manuals; refined national CO_2 storage assessments through characterization field projects; and trained nearly 3,000 students through the Regional Carbon Sequestration Training Centers. NETL's Carbon Storage R&D Program has made significant progress in establishing a solid understanding of CCUS-related infrastructure throughout North America. Ultimately, the implementation of small- and large-volume storage tests and regional characterization efforts as served to verify the best technologies to use in future application of CCUS systems in the United States and Canada. Future field testing will continue to enhance these technologies and allow for better understanding of CO_2 storage across various geologic reservoir types. Furthermore, providing CCUS training opportunities allows for an increased and better trained workforce well-versed in the necessary best practices needed to make an impact to future CCUS operations throughout the United States and worldwide.

Appendix A: NETL's Assessment of Basalt and Organic-rich Shale Formations



Appendix A Figure. Distribution of basalt formations (left) and organic-rich shales (right) throughout the United States and Canada

Basalt Formations: The relatively large amount of potential storage resource in basalts, along with their geographic distribution, makes them an important formation type for possible CO_2 storage, particularly in the Pacific Northwest and the southeastern United States. Basalt formations are geologic formations of solidified lava. 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 from the atmosphere permanently. 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. However, CO_2 storage in basalt formations is an area of current research, and before basalt formations can be considered viable storage targets, a number of questions related to the basic geology, CO_2 trapping mechanisms and their kinetics, and monitoring and modelling tools need to be addressed. The map in this Appendix A presents the locations of these potential future storage opportunities, but DOE currently has no CO_2 storage resource values for basalt formations [4].

Organic-rich Shale Formations: Shales are formed from silicate minerals that are degraded into clay particles that accumulate over millions of years in areas of still water. The plate-like structure of these clay particles causes them to accumulate in a flat manner, resulting in rock layers with extremely low permeability in the vertical direction. Therefore, shales are most often used in a geologic storage system as a confining seal or caprock. If the horizontal permeability in shales is preferentially increased through engineering, CO_2 storage becomes feasible. Recent technological advances in the form of horizontal drilling and hydraulic fracturing have increased energy sector interest in organic-rich shales for natural gas production. With horizontal drilling and hydraulic fracturing, operators are basically engineering the 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 in much the same way as ECBM recovery. More research is needed on organic-rich shales to fully understand CO_2 storage potential in these formations [4].

References

[1] National Energy Technology Laboratory. 2011. Carbon Sequestration Program: Technology Program Plan. http://www.netl.doe.gov/technologies/carbon_seq/refshelf/2011_Sequestration_Program_Plan.pdf

[2] National Energy Technology Laboratory. 2012. 2012 United States Carbon Utilization and Storage Atlas (Atlas IV) (DOE/NETL-2012/1589).

[3] National Energy Technology Laboratory. 2010. Best Practices for: Site Screening, Site Selection, and Initial Characterization for Storage of CO2 in Deep Geologic Formations. Document Number: DOE/NETL-401/090808. http://www.netl.doe.gov/technologies/carbon_seq/refshelf/BPM-SiteScreening.pdf

[4] National Energy Technology Laboratory. 2010. Carbon Sequestration Atlas of the United States and Canada – Third Edition. http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasIII/index.html

[5] World Resources Institute (WRI). 2008. CCS Guidelines: Guidelines for Carbon Dioxide Capture, Transport, and Storage. Washington, DC: WRI.

[6] Rodosta, T., Litynski, J., Plasynski, S., Spangler, L., Finley, R., Steadman, E., Ball, D., Hill, G., McPherson, B., Burton, E., and Vikara, D. 2010. U.S. Department of Energy's Regional Carbon Sequestration Partnership Initiative: Update on Validation and Development Phases. Energy Procedia. Proceedings of the 10th International Conference on Greenhouse Gas Control Technologies (GHGT-10), September 19–23, 2010. Amsterdam, The Netherlands.

[7] National Energy Technology Laboratory. Carbon Storage Website – ARRA Site Characterization Projects. Available online: http://www.netl.doe.gov/technologies/carbon_seq/infrastructure/arrasitechar.html

[8] Litynski, J., Plasynski, S., Spangler, L., Finley, R., Steadman, E., Ball, D., Nemeth, K., McPherson, B., and Myer, L. 2009. U.S. Department of Energy's Regional Carbon Sequestration Partnership Program: Overview. Energy Procedia 1(2009) 3959-3967.

[9] National Energy Technology Laboratory. Carbon Storage Website – Regional Carbon Sequestration Partnership. Available online: http://www.netl.doe.gov/technologies/carbon_seq/infrastructure/rcsp.html

[10] Schroeder, L., and Ozdemir, R. 2001. Sequestration of Carbon Dioxide in Coal Seams. Proceedings in the First National Conference on Carbon Sequestration.

[11] National Energy Technology Laboratory. Carbon Storage Website – Best Practices Manuals. Available online: http://www.netl.doe.gov/technologies/carbon_seq/infrastructure/bestpractices.html

[12] National Energy Technology Laboratory. Carbon Storage Website – ARRA Regional Carbon Sequestration Training Centers. Available online: http://www.netl.doe.gov/technologies/carbon_seq/infrastructure/training.html