DOE/NETL-2015/1711

2014 TECHNOLOGY READINESS ASSESSMENT—OVERVIEW

—A CHECKPOINT ALONG A CHALLENGING JOURNEY

JANUARY 2015

CLEAN COAL RESEARCH PROGRAM

United States Department of Energy | Office of Fossil Energy

DISCLAIMER

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ABBREVIATIONS

ADM	Archer Daniels Midland Company
AEC	Anode-Electrolyte-Cathode
AIChE	American Institute of Chemical Engineers
APCI	Air Products and Chemicals, Inc.
ARRA	American Recovery and Reinvestment Act of 2009
ASME	American Society of Mechanical Engineers
°C	degrees Celsius
$CaCO_3$	calcium carbonate
CCPI	Clean Coal Power Initiative
CCRP	Clean Coal Research Program
CCS	carbon capture and storage
CO_2	carbon dioxide
DoD	Department of Defense
DOE	Department of Energy
ECBM	enhanced coalbed methane
EOR	enhanced oil recovery
EPA	Environmental Protection Agency
EPAct	Energy Policy Act of 2005
FE	Office of Fossil Energy
FPM	Federal Project Manager
FWP	field work proposal
FY	fiscal year
GHG	greenhouse gas
GPRA	Government Performance and Results Act
GSSC	Geologic Sequestration Site Characterization
GSTR	Geologic Sequestration Training and Research
H_2	hydrogen
H_2O	water
ICCS	Industrial Carbon Capture and Storage
IEA	International Energy Agency
IRL	Integration Readiness Level
ITM	ion transport membrane
LIDAR	laser-induced differential absorption radar
MOF	metal organic framework
MVA	monitoring, verification, accounting, and assessment
MW	megawatt
MWe	megawatt-electric
NASA	National Aeronautics and Space Administration
NCCC	National Carbon Capture Center
NETL	National Energy Technology Laboratory
OMB	Office of Management and Budget
PPA	Post-Project Assessment
R&D	research and development
RD&D	research, development, and demonstration
SBIR	Small Business Innovation Research
SCC	Strategic Center for Coal
scfm	standard cubic feet per minute
SCS	Southern Company Services, Inc.
SMR	steam methane reformer
SOFC	solid oxide fuel cell
SRL	Systems Readiness Level
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
VSA	vacuum swing adsorption
VUE	Visual User Environment

INTRODUCTION

Building on the initial formal Technology Readiness Assessment (TRA) of the Office of Fossil Energy's (FE's) Clean Coal Research Program (CCRP) that was conducted in fiscal year 2012 (FY12),[1] and consistent with ongoing efforts to supply policy makers with the most current, concise information to enable them to better gauge the maturity of carbon capture and storage (CCS) technologies, the National Energy Technology Laboratory (NETL) has undertaken this FY14 TRA of the CCRP's "key technologies." As in FY12, the Department of Energy-Fossil Energy Technology Readiness Assessment Guide (DOE-FE Guide[2]) served as the basis for a detailed, structured evaluation of the maturity of NETL's key technologies. This effort involved a three-step process:

- Establish a standard set of benchmarks.
- Conduct a formal assessment of the ongoing research, development, and demonstration (RD&D) efforts being supported by FE's CCRP using the Technology Readiness Level (TRL) evaluation discipline.
- Publicly report the results of the TRA evaluation.

The FY14 assessment was focused on the research and development (R&D) program area of the CCRP and the entire portfolio of projects was reviewed and considered for assessment as part of the evaluation process. Additionally, due to improvements in scoring, some projects, including field work proposals (FWPs), were divided into tasks; all tasks not excluded due to the following criteria were considered to be individual projects. All projects awarded by or active on October 1, 2013, were scored with the following exclusions:

- Systems analysis projects
- Small Business Innovation Research (SBIR) projects
- Industrial Carbon Capture and Storage (ICCS) Area 2 projects
- Geologic Sequestration Site Characterization (GSSC) projects
- Geologic Sequestration Training and Research (GSTR) projects
- Support FWPs

As of October 1, 2013, there were 423 active projects within the CCRP R&D portfolio. This portfolio had a value of approximately \$3.5 billion composed of a \$2.6 billion DOE share and \$0.9 billion private-sector share. For the FY14 TRA, 349 projects and tasks were scored with an approximate value of \$2.5 billion (\$1.9 billion DOE share), representing over 72 percent of the total value of the R&D component of the CCRP. The results of the FY14 TRA are presented in this overview report. For more details pertaining to the FY14 assessment process, please see the FY14 TRA comprehensive report.

BACKGROUND

Today the energy resources that fuel our nation's economy are 82 percent fossil-based, with coal playing a significant role. Of the roughly 98 quads of energy our economy consumes each year, our coal and natural gas resources satisfy nearly one-half of this demand while affordably producing over two-thirds of our electricity.[3] All segments of U.S. society rely heavily on America's existing multibillion-dollar investment in its highly reliable and affordable fossil-based utility, industrial, commercial, transportation, and residential energy infrastructure. However, the continued use of coal faces a strategically important challenge. While demand for electricity continues to escalate, there are significant public concerns regarding coal-based emissions, particularly carbon dioxide (CO_2) and its relation to climate change. This is a global issue that requires worldwide attention, and advanced technological solutions are required. The most recent Environmental Protection Agency (EPA) regulations for coal-fueled power plants create significant challenges for these plants to control carbon emissions yet remain affordable in today's economy.

To meet this challenge, the Office of Fossil Energy's CCRP responds specifically to various policy-related drivers including Presidential initiatives, Secretarial goals, the Energy Policy Act of 2005 (EPAct), and the American Recovery and Reinvestment Act of 2009 (Recovery Act or ARRA). In addition, FE's strategies reflect congressional testimony provided by DOE rep-

1 The FY12 Technology Readiness Assessment can be found at: http://www.netl.doe.gov/File%20Library/Research/Coal/Reference%20Shelf/TRL-Comprehensive-Report_121112_FINAL_1.pdf

2 U.S. Department of Energy, Office of Fossil Energy. *DOE-FE Technology Readiness Assessment Guide—DRAFT*. September 2011. Accessed October 2013.

3 United States Energy Information Administration. *Monthly Energy Review*. July 2014. Accessed August 2014. http://www.eia.gov/totalenergy/data/monthly/#electricity

resentatives in response to these drivers. Ultimately, the CCRP is responsive to the DOE's 2014 Strategic Plan[4] and the FY14 Congressional Budget Request, which provide guidance for all activities within DOE. A summary of specific CCRP drivers and associated goals and targets follows.

PRESIDENTIAL INITIATIVES

In 2009, President Obama articulated a priority energy goal for his Administration: "catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies." Related to this goal, the Administration established the following targets:

- Reduce energy-related greenhouse gas (GHG) emissions by 17 percent by 2020[5] and 83 percent by 2050, from a 2005 baseline
- Generate 80 percent of America's electricity from clean energy sources by 2035

On February 3, 2010, President Obama established an Interagency Task Force on Carbon Capture and Storage composed of representatives from 14 Executive departments and Federal agencies. As stated in the August 2010 task force report:

> "While CCS [carbon capture and storage] can be applied to a variety of stationary sources of CO_2, its application to coal-fired power plant emissions offers the greatest potential for GHG reductions. Coal has served as an important domestic source of reliable, affordable energy for decades, and the coal industry has provided stable and quality high-paying jobs for American workers. At the same time, coal-fired power plants are the largest contributor to U.S. greenhouse gas emissions, and coal combustion accounts for 40 percent of global CO_2 emissions from the consumption of energy. EPA and Energy Information Administration assessments of recent climate and energy legislative proposals show that, if available on a cost-effective basis, CCS can over time play a large role in reducing the overall cost of meeting domestic emissions reduction targets. By playing a leadership role in efforts to develop and deploy CCS technologies to reduce GHG emissions, the United States can preserve the option of using an affordable, abundant, and domestic energy resource, help improve national security, help to maximize production from existing oil fields through enhanced oil recovery (EOR), and assist in the creation of new technologies for export."

In June 2013, President Obama issued the Climate Action Plan to cut the carbon pollution that is linked to climate change and affects public health. The plan, which consists of a wide variety of executive actions, has three key pillars:

- Cut Carbon Pollution in America
- Prepare the United States for the Impacts of Climate Change
- Lead International Efforts to Combat Global Climate Change and Prepare for Its Impacts

The Climate Action Plan outlines additional steps the Administration will take—in partnership with States, local communities, and the private sector—to continue on a path to meeting the President's 2020 goal.

DOE STRATEGIC PLAN

In March 2014, DOE issued its Strategic Plan 2014–2018, which provides the following additional guidance to the CCRP.

Mission

Enhance U.S. security and economic growth through transformative science, technology innovation, and market solutions to meet our energy, nuclear security, and environmental challenges.

Strategic Objectives

- **STRATEGIC OBJECTIVE 1—**Advance the goals and objectives in the President's Climate Action Plan by supporting prudent development, deployment, and efficient use of "all of the above" energy resources that also create new jobs and industries.

4 United States Department of Energy. *Strategic Plan*. March 2014. Accessed October 2013. http://energy.gov/sites/prod/files/2014/04/f14/2014_dept_energy_strategic_plan.pdf

5 On November 12, 2014, during his visit to China, President Obama announced that the United States has set a new goal of reducing its net greenhouse gas emissions by 26 to 28 percent below 2005 levels by the year 2025. This builds on the current target of a 17 percent reduction below that baseline by 2020.

- **STRATEGIC OBJECTIVE 2**—Support a more economically competitive, environmentally responsible, secure and resilient U.S. energy infrastructure.
- **STRATEGIC OBJECTIVE 3**—Deliver the scientific discoveries and major scientific tools that transform our understanding of nature and strengthen the connection between advances in fundamental science and technology innovation.

CCRP ALIGNMENT WITH THE DEPARTMENT'S GOALS

Government Performance and Results Act Endpoint Performance Targets

The RD&D performance of FE's CCRP RD&D portfolio is measured using a Government Performance and Results Act (GPRA) methodology to quantify progress against pre-established targets.

- **ENDPOINT PERFORMANCE TARGET 1**—CCS Demonstrations: Operations initiated at a minimum of five commercial-scale CCS demonstrations by 2019 including the Clean Coal Power Initiative (CCPI), FutureGen 2.0, and the Industrial CCS Demonstration projects (funded by both annual appropriations and the American Recovery and Reinvestment Act). At least two of the five demonstrations to initiate operations by 2019 will be CCPI projects.
- **ENDPOINT PERFORMANCE TARGET 2**—Carbon Capture and Advanced Energy Systems: Advanced Energy Systems with CO_2 capture at no more than $40 per tonne of CO_2 captured by 2020.
- **ENDPOINT PERFORMANCE TARGET 3**—Carbon Storage: Inject 9.0 million metric tons of CO_2 in large-volume field test sites representing different storage classes, since January 2009, to demonstrate and monitor for the formations' capacity to permanently, economically, and safely store carbon dioxide. A long-term goal is to ensure the cost-effective ability to measure and account for 99 percent of injected CO_2 in all storage types while minimizing the environmental footprint of carbon storage activities.

AMERICAN RECOVERY AND REINVESTMENT ACT

The Recovery Act provided an additional $3.4 billion for FE RD&D to expand and accelerate the commercial deployment of CCS technology. Through Fossil Energy funding under annual appropriations and the Recovery Act, DOE is expediting the development of advanced technologies and the demonstration of CCS to meet future energy needs worldwide.

RESEARCH STRATEGY

In response to the program drivers noted above, DOE has adopted a mission that emphasizes, among other priorities, technology development capable of realizing rapid commercialization of efficient, economical solutions that minimize CO_2 emissions to the atmosphere. The primary mission of FE is to ensure that the United States can continue to rely on clean, affordable energy from our traditional fuel resources. FE has for many years pursued a national priority to develop advanced clean coal technology and has kept such technologies flowing through the RD&D pipeline. The current emphasis of the CCRP, which is administered by FE and implemented by NETL, is designed to eliminate environmental concerns related to coal use by developing a portfolio of innovative, near-zero-emissions technologies. Conducted in partnership with the private sector, the CCRP's RD&D efforts focus on maximizing the efficiency and environmental performance of advanced coal technologies, while minimizing development and deployment costs.

The CCRP links to the March 2014 DOE Strategic Plan and supports the achievement of DOE's mission and applicable goals by deploying a strategy focused on the following:

- Accelerating energy innovation through pre-competitive R&D
- Demonstrating and deploying clean energy technologies
- Facilitating technology transfer to industry
- Establishing technology test beds and demonstrations
- Leveraging partnerships to expand the impact of the Federal investments

At a more discrete level, the CCRP complies with Federal assessment mechanisms, including GPRA and FE's Annual Operating Plan.

The CCRP's contributions to the achievement of DOE's mission include the RD&D of innovative coal technologies that are highly efficient, achieve near-zero emissions (including CO_2), and are commercially deployable in a competitive energy market. The baseline CCRP consists of two distinct program areas: (1) CCS and Power Systems R&D and (2) CCS Demonstrations. Each program area has specific goals that contribute to DOE's carbon reduction portfolio, either through direct capture and storage of GHGs or through significant gains in efficiency. Although the CCRP conducts demonstration projects to ensure that various technologies are fully ready for commercial deployment, to have reached the demonstration stage for advancement, technologies must have cleared a series of lower level R&D hurdles. It is these lower level TRL stages, generally considered to be TRL 2 through TRL 6, that are the subject of this assessment. That is, this assessment focused only on technologies in the CCS and Power Systems R&D program area, since technologies that are components of the CCS Demonstrations program area have all cleared a series of lower level TRL hurdles and have attained a high degree of maturation.

A number of technical and economic challenges must be overcome before cost-effective solutions can be implemented throughout the United States to address climate change concerns associated with fossil energy-based electric power production. Specifically, the integration of CCS with coal-fired power generation at commercial scale needs to be demonstrated, and the permanence and safety of CO_2 storage must be assured. Capital and operating costs must be significantly reduced so that CCS technology can be deployed on both new and existing facilities for a wide range of fuel types and geological storage settings. Overcoming these challenges requires not only adequate funding, but innovative strategies that must be developed in conjunction with the private sector and DOE's academic partners. To achieve this end, DOE is addressing the key challenges that confront the wide-scale commercial deployment of CCS through industry/Government/academic cooperative research on cost-effective capture, storage, and power plant efficiency-improvement technologies.

CCRP STRUCTURE

The CCRP is implemented by NETL's Strategic Center for Coal (SCC) and is organized into two major program areas: CCS and Power Systems R&D and CCS Demonstrations. Under the CCS and Power Systems R&D program area, the SCC conducts coal-related research in four subprograms:

- **ADVANCED ENERGY SYSTEMS** focuses on developing advanced combustion systems, advanced gasification systems, stationary power fuel cells, and improved gas turbines for future coal-based combined-cycle plants that are cleaner, more efficient, and capture carbon.
- **CARBON CAPTURE** develops technologies to lower the costs of carbon capture from both pre-combustion and post-combustion systems.
- **CARBON STORAGE** manages the development of systems to provide information on engineered geologic storage approaches to improve injectivity, efficiency, and containment, and to develop advanced instrumentation and simulation tools to measure and validate geologically stored carbon.
- **CROSSCUTTING RESEARCH** develops technologies for improving the efficiency and environmental performance of advanced coal power systems through the use of modeling, advanced simulation techniques, novel sensors, process control, and advanced materials.

These subprograms are further subdivided into Technology Areas and each Technology Area—which is supported through multiple projects—is organized to pursue the development of key technologies. The flow of technology and its relative stage of development that is employed by the CCRP to accomplish its mission to develop technology and make it ready for its potential commercial deployment are depicted in Figure 1. The CCRP is fundamentally an applied research program, and because TRL 1 reflects basic research, the CCRP is generally focused on advancing technology from TRL 2 through TRL 6 for the CCS and Power Systems R&D program area.

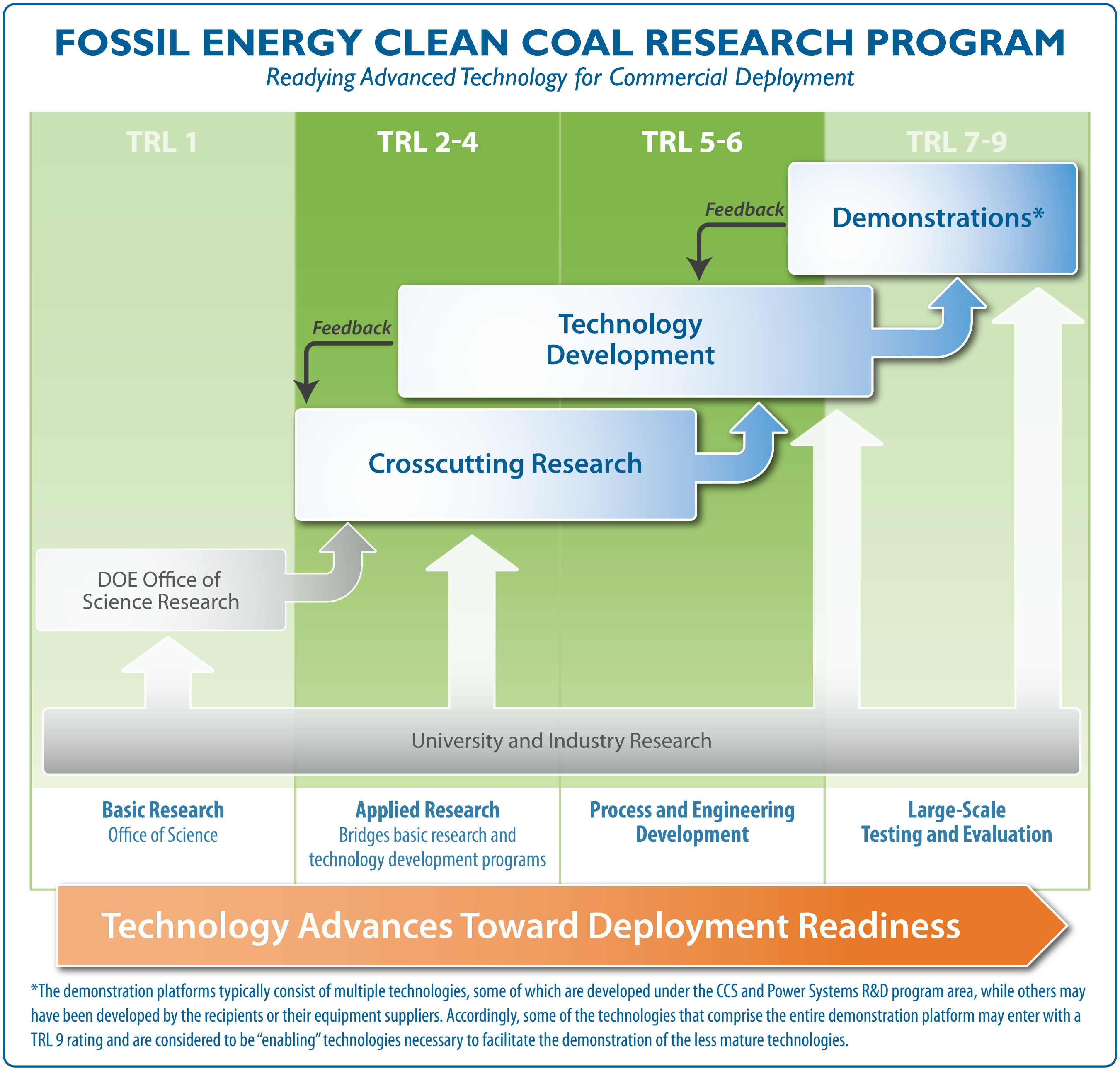


Figure 1. Schematic of DOE-FE Technology Readiness Levels

Once engineering-scale models or prototypes have been tested in a relevant environment, technologies within the R&D portfolio can be advanced to the CCS Demonstrations program area, where they are tested at scale to advance their readiness for commercial deployment. Technology availability for advancement is based on technology performance expectations, funding availability, demonstration program area priorities, and other factors. While R&D projects typically focus on a single key technology, the demonstration projects frequently serve as a platform to advance multiple key technologies. This overview report focuses primarily on the TRA of the CCS and Power Systems program area; however, an overview of the TRA approach to technologies in the CCS Demonstrations program area is included for completeness.

TECHNOLOGY READINESS ASSESSMENT

In FY12, NETL developed standard benchmarks and performed the first assessments of key technologies within its research portfolio (FY12 TRA report). This FY14 TRA overview report provides a summary of the second analysis that was conducted and the findings that resulted.

NETL has a long and rich history of performing various allied forms of technology assessments, including rigorous, comprehensive independent Peer Reviews of the technologies under investigation. The associated sidebar, shown on the following page, provides additional details concerning these efforts and depicts examples of recent products.

TRA PROCESS

The TRA process is defined as a "systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology."[6] TRLs do not establish a pass/fail grade, but rather serve to methodically assess the state of the technology development spanning progress from early research on basic principles through large-scale testing and evaluation prior to commercial deployment. Technology development typically advances over a multi-year period and designs are incrementally refined until a suitably sized, successful demonstration is completed. TRLs are particularly useful in establishing a consistent set of terminology and a rigorous evaluation process that can be used to clearly establish a technology's current state of progress. This process is widely used in industry and is becoming a common practice within Government agencies. By more clearly understanding the current state and assessing the degree of development that yet remains, TRLs emerge as a useful tool in the planning of future RD&D activities. The DOE TRA Guide[7] provided the foundation for the assessment of CCRP R&D projects conducted by NETL.

The TRL approach was originally developed by the National Aeronautics and Space Administration (NASA) for its Space Shuttle program and later adapted by the U.S. Department of Defense (DoD) for use in its defense systems acquisition. Just as DoD restructured NASA's entire set of TRL definitions and descriptions to better suit its mission, DOE similarly tailored the TRL definitions and descriptions so that they would be applicable to energy-research-related technologies. The TRA Guide[8] developed by DOE reviews the NASA and DoD methods and, although originally developed to be applicable to nuclear-fuel-waste technology, provides a general process reference suitable for guiding the assessment of the technologies being developed in the DOE-FE CCRP, which is currently focused on development of advanced coal-fueled power systems with carbon capture, utilization, and storage.

To ensure sound, consistent, and reliable results, a diverse and highly qualified team was assembled and directed to complete the CCRP portfolio assessment in accordance with the DOE-FE Guide. The assessment team, which consisted of NETL Federal Project Managers (FPMs), subject matter experts, and individuals knowledgeable in the execution of TRAs,[9] carried out the process in a manner that considered the entire spectrum of projects in the R&D portion of the FE CCRP.

The core TRA Team was expanded to include individuals with project-specific knowledge and divided into 14 Key Technology Area Assessment Teams. This approach helped ensure consistency and standardization while also supporting a reasonable timeframe for completion of the effort. Each Key Technology Area Assessment Team had a full complement of individuals with project and technology knowledge, relevant experience, and TRL proficiency. This core and expanded team approach, coupled with a standard assessment process, which included several levels of consensus, was designed to ensure consistent and technically sound results across the entire CCRP R&D portfolio.

After the active project set was determined and the key technologies under development were associated with their corresponding Technology Area (or Areas), the subset of active projects that met TRA scoring applicability criteria was determined. Primary assessors were then assigned to each project in this abridged set. A comprehensive set of information was gathered by the team for each project and technology of interest. The primary assessors, who were expected to fully

6 Mankins, J., *Technology Readiness Level White Paper*. 1995, rev. 2004. Accessed October 2013. http://www.artemisinnovation.com/images/TRL_White_Paper_2004-Edited.pdf

7 United States Department of Energy. *DOE Technology Readiness Assessment Guide*. DOE G 413.3-4A. September 15, 2011. Accessed October 2013. https://www.directives.doe.gov/directives/0413.3-EGuide-04a/view

8 United States Department of Energy. *DOE Technology Readiness Assessment Guide*. DOE G 413.3-4A. September 15, 2011. Accessed October 2013. https://www.directives.doe.gov/directives/0413.3-EGuide-04a/view

9 Such individuals have established proficiency by applying TRL methodologies within other DOE Offices (e.g., DOE's Office of Environmental Management), other Federal Government agencies (e.g., NASA), and/or industry.

understand and become conversant with the TRL definitions and descriptions provided in the DOE-FE Guide, reviewed the available project and technical information. An assessment of the status or maturity of the key technologies associated with each project was performed and an initial TRL determination made. The primary assessor was responsible for drafting an assessment summary document that provided all pertinent information, including the initial TRL.

The primary assessor then reviewed the draft assessment summary sheets for each assessed project with the FPM assigned to that project, and they worked together collaboratively to plug gaps and address outstanding questions. When the assessment summary drafts were complete for a given key technology, the primary assessor scheduled a consensus meeting with the full assessment team. Each assessor presented the project summaries, provided an explanation that justified the assigned TRL, and facilitated discussion among team members. The assessment team developed a consensus TRL for each project, and the project summary drafts were revised and shared with the FPM. Consensus was confirmed with the FPM or the score was adjusted if necessary, and the project summaries were finalized. Project summaries were completed for each selected project and covered each associated key technology, providing the pertinent information. Consensus meetings were held with the NETL Technology Managers for each selected key technology in their purview. Project summaries were changed as necessary to reflect the results of the consensus process.

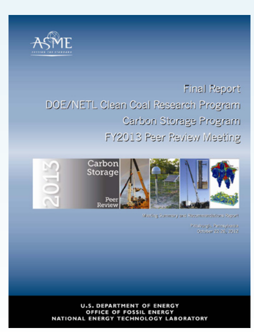
Final project summaries were distributed to the applicable Principal Investigators with a request for feedback and concurrence. In general the feedback was both responsive and timely. In a few cases, the Principal Investigators proposed an increase in the TRL rating. Following discussions, consensus was reached.

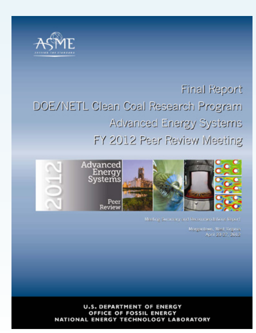
The nature of the CCS and Power Systems R&D portion of the CCRP is to pursue research at the lower and mid-level range of the readiness scale. The goal of the assessment effort is to identify the current state of readiness of the R&D portfolio's key technologies. The detailed technology assessment and scoring followed the process depicted in *Figure 2: Process Flow for Conducting TRA*, shown on page 13 of this overview report.

PEER REVIEWS—ASSESS CLEAN COAL RESEARCH PROGRAM TECHNOLOGIES

While the Technology Readiness Assessment (TRA) process is one specific tool that can provide essential feedback on the effectiveness of ongoing research aimed at accomplishing a program's mission, goals, and strategies, FE relies on a comprehensive suite of tools to evaluate its programs, ensure relevance to national energy needs, and guide decisions at the project and program level. NETL and its SCC have implemented a process in response to the DOE requirements for conducting technology evaluations and Peer Reviews of its coal R&D efforts. Consistent with guidance from the Office of Management and Budget (OMB) bulletins and circulars on Peer Reviews, and the U.S. Department of Energy's Strategic Plan, biannual Peer Reviews are performed. FE routinely commissions the independent review of Technology Areas in accordance with the Department's Guide for Managing General Program Evaluation Studies to assess the status of the research, accomplishments, and planned activities. Peer Reviews conducted by independent experts from the American Society of Mechanical Engineers (ASME), American Institute of Chemical Engineers (AIChE), International Energy Agency (IEA), and ASM International have been completed spanning all program areas of the CCRP. The results of these reviews and a summary of the findings developed by review panels can be found on the NETL website under Technologies » Coal and Power Systems; these results are routinely posted and made publicly available as new reviews are completed. All recommendations resulting from these reviews are evaluated, addressed, and resolved via the development of detailed mitigation strategies and actions that are recorded and tracked through completion. Peer Reviews improve the overall quality of the technical aspects of R&D activities and enhance project-related activities such as utilization of resources, project and financial management, and commercialization. In addition, Peer Reviews allow the DOE to gain industry acceptance of the SCC Office of Coal and Power Systems' program R&D efforts by communicating the goals and objectives that are supported by their various program portfolios. The most recent Peer Reviews include Hydrogen Turbines and Solid Oxide Fuel Cells. More information can be found at: www.netl.doe.gov/research/coal/publications/peer-reviews

> "In order for us to maintain our edge, we've got to protect our rigorous peer review system and ensure that we only fund proposals that promise the biggest bang for taxpayer dollars."
>
> **President Obama**, April 2013
>
> Remarks on the 150th Anniversary of the National Academy of Sciences





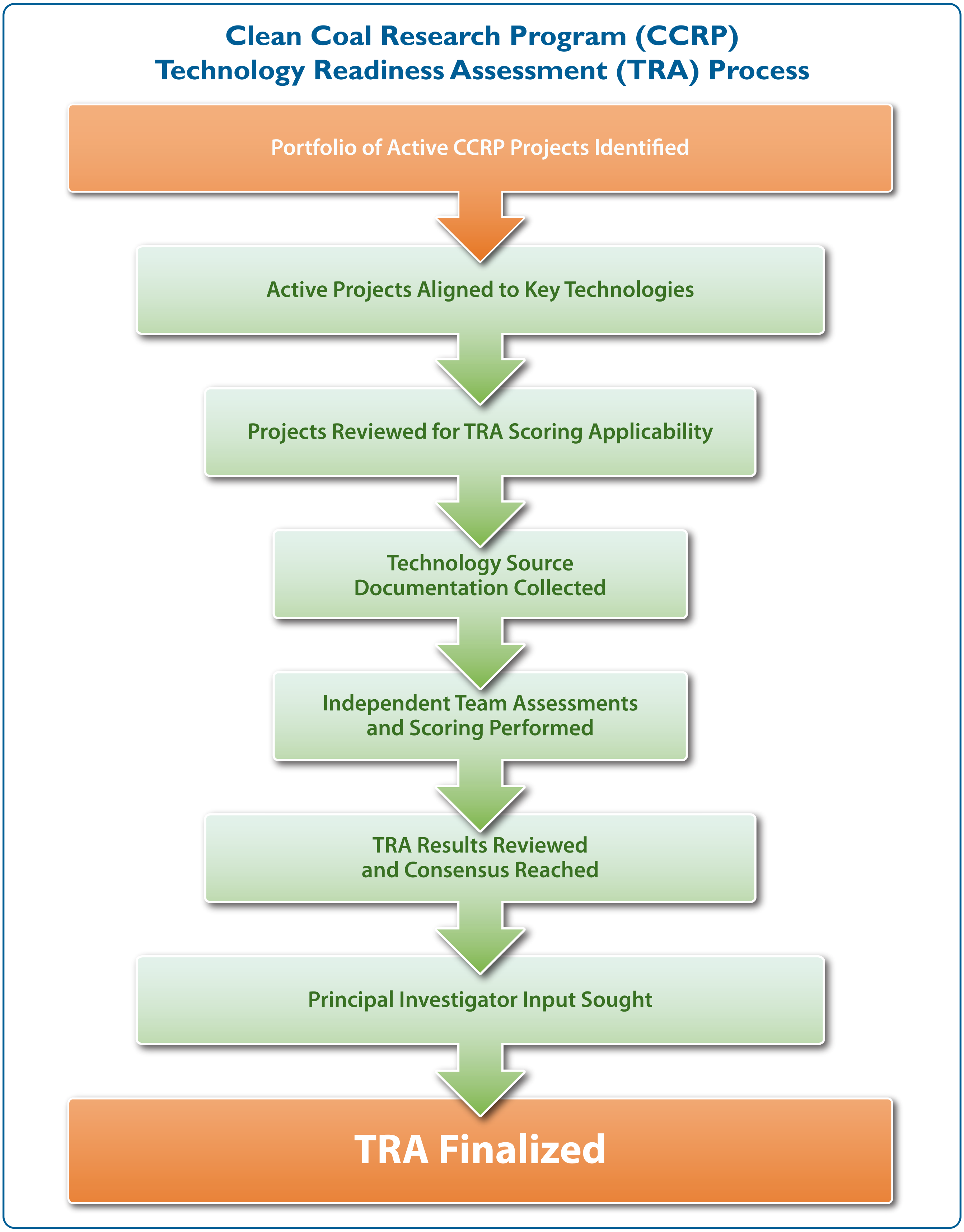


Figure 2. Process Flow for Conducting TRA

TRA METHODOLOGY

TRA DEFINITIONS

For the purposes of this assessment, the TRL definitions and descriptions in DOE's TRA Guide were customized to make them suitable for application to advanced coal-fueled power systems. Building upon the guidelines established in the DOE's TRA Guide, a Department of Energy-Fossil Energy Technology Readiness Assessment Guide (DOE-FE Guide[10]) was developed by the Office of Fossil Energy to outline a comprehensive, consistent process for assessing the maturity (TRL) of the diverse portfolio of technologies currently under development. Tables 1 and 2 provide the DOE-FE TRL definitions and descriptions used in this 2014 Technology Readiness Assessment. Because of the distinctly different system functions and operating environments, and with advanced power-generation and carbon storage systems having such markedly different end-state deployment characteristics, it was necessary to develop separate TRL readiness terminology and scales. Refer to Table 1 for TRL definitions and descriptions for advanced power-generation systems and to Table 2 for technologies for carbon storage. Although the definitions imply a linear progression in technology advancement, the use of advanced simulation may support a nonlinear progression where technology development bypasses or skips a TRL. For several Technology Areas, Basis of Application documents were developed and utilized to provide additional guidance related to the interpretation of TRL definitions and descriptions.

Table 1. **DOE-FE Plant Technology TRL Definitions and Descriptions**

TRL	DOE-FE Definition	DOE-FE Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology (e.g., individual technology components have undergone laboratory-scale testing using bottled gases to simulate major flue gas species at a scale of less than 1 scfm).
4	Component and/or system validation in a laboratory environment	A bench-scale prototype has been developed and validated in the laboratory environment. Prototype is defined as less than 5 percent final scale (e.g., complete technology process has undergone bench-scale testing using synthetic flue gas composition at a scale of approximately 1–100 scfm).
5	Laboratory-scale similar-system validation in a relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Prototype is defined as less than 5 percent final scale (e.g., complete technology has undergone bench-scale testing using actual flue gas composition at a scale of approximately 1–100 scfm).
6	Engineering/pilot-scale prototypical system demonstrated in a relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. Pilot or process-development-unit scale is defined as being between 0 and 5 percent final scale (e.g., complete technology has undergone small pilot-scale testing using actual flue gas composition at a scale equivalent to approximately 1,250–12,500 scfm).
7	System prototype demonstrated in a plant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Final design is virtually complete. Pilot or process-development-unit demonstration of a 5–25 percent final scale or design and development of a 200–600 MW plant (e.g., complete technology has undergone large pilot-scale testing using actual flue gas composition at a scale equivalent to approximately 25,000–62,500 scfm).
8	Actual system completed and qualified through test and demonstration in a plant environment	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include startup, testing, and evaluation of the system within a 200–600 MW plant CCS operation (e.g., complete and fully integrated technology has been initiated at full-scale demonstration including startup, testing, and evaluation of the system using actual flue gas composition at a scale equivalent to approximately 200 MW or greater).
9	Actual system operated over the full range of expected conditions	The technology is in its final form and operated under the full range of operating conditions. The scale of this technology is expected to be 200–600 MW plant CCS operations (e.g., complete and fully integrated technology has undergone full-scale demonstration testing using actual flue gas composition at a scale equivalent to approximately 200 MW or greater).

10 U.S. Department of Energy, Office of Fossil Energy. *DOE-FE Technology Readiness Assessment Guide—DRAFT*. September 2011. Accessed October 2013.

Table 2. **DOE-FE CO_2 Storage Technology TRL Definitions and Descriptions**

TRL	DOE-FE Definition	DOE-FE Description for CO_2 Storage
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples include analytic and laboratory studies to confirm the potential practical application of basic processes and methods to geologic storage.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. Components may be tested with simulants.
4	Component and/or system validation in a laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in a laboratory and testing with a range of simulants.
5	Laboratory-scale similar-system validation in a relevant environment	Laboratory validation of system/subsystem components. Laboratory validation testing of geologic storage processes, subsystems and/or subsystem components under conditions representative of in situ operation. Subsystem and/or component configuration is similar to (or matches) the final application in almost all respects. Validation testing involves measurements under in situ operating conditions to assess performance of the process, subsystem and/or component. Planning and design are undertaken for prototype system verification.
6	Engineering/pilot-scale, prototypical system demonstrated in a relevant environment	Prototype system verified. Prototype field pilot testing of geologic storage system or subsystem in relevant geologic environments. Geologic characteristics, including rock type and contained fluids, depth, pressure, and temperature are relevant to final scale. Pilot scale involves injection of a sufficient amount of CO_2 to verify design performance of system or subsystem and components. System configured to enable pilot-scale testing, which involves measurements and operations specific to assessing performance of the system and/or subsystem and subsystem components. Performance testing relevant to the lifecycle of a storage project, including site characterization, injection, and post-injection monitoring and closure.
7	System prototype demonstrated in a plant environment	Integrated pilot system demonstrated. Geologic storage system prototype tested at pilot scale for a type of depositional environment (e.g., saline fluvial deltaic) or storage type (e.g., EOR or enhanced coalbed methane [ECBM]). Pilot scale involves injection of a few hundred tonnes[6] to several hundred thousand tonnes. System configured to enable pilot-scale testing, which involves measurements and operations specific to assessing performance of the system, subsystem, and subsystem components. Performance testing is relevant to each stage of the full lifecycle of a storage project, including site characterization, injection, and post-injection monitoring and closure. Planning and design are undertaken to test and demonstrate a full-scale system.
8	Actual system completed and qualified through test and demonstration in a plant environment	System tested and demonstrated at final scale. This TRL represents the end of technology development for a geologic storage system for a type of depositional environment (e.g., saline fluvial deltaic) or storage type (e.g., EOR or ECBM). The complete geologic storage system is tested at final scale in a demonstration. Final scale involves injection of >1 million tonnes per year. System configured to enable final-scale testing, which involves measurements and operations specific to assessing performance of the system, subsystem, and subsystem components. Performance testing is relevant to each stage of the full lifecycle of a storage project, including site characterization, injection, and post-injection monitoring and closure.
9	Actual system operated over the full range of expected conditions	System proven and ready for final-scale geologic storage. Geologic storage system is proven through successful operations at full scale for a type of depositional environment (e.g., saline fluvial deltaic) or storage type (e.g., EOR or ECBM). Full scale involves injection of >1 million tonnes per year. System configured for final-scale deployment, including considerations of cost. Operations include full lifecycle of the storage project, including site characterization, injection, and post-injection monitoring and closure.

TRA IMPLEMENTATION

NETL's FY14 TRA focused on "key technologies" and is organized consistent with the budget structure provided via the FY14 congressional budget appropriations. The CCRP is thus subdivided into four distinct subprograms: Advanced Energy Systems, Carbon Capture, Carbon Storage, and Crosscutting Research, as depicted in Figure 3.

11 Among key stakeholders in the carbon capture and storage communities, tonnage quantities are generally expressed as metric tons (tonnes). That protocol will be followed throughout this document. However, for other program components where its use is more customary, U.S. "tons" are used. One tonne is equal to 1,000 kg or 2,205 pounds.

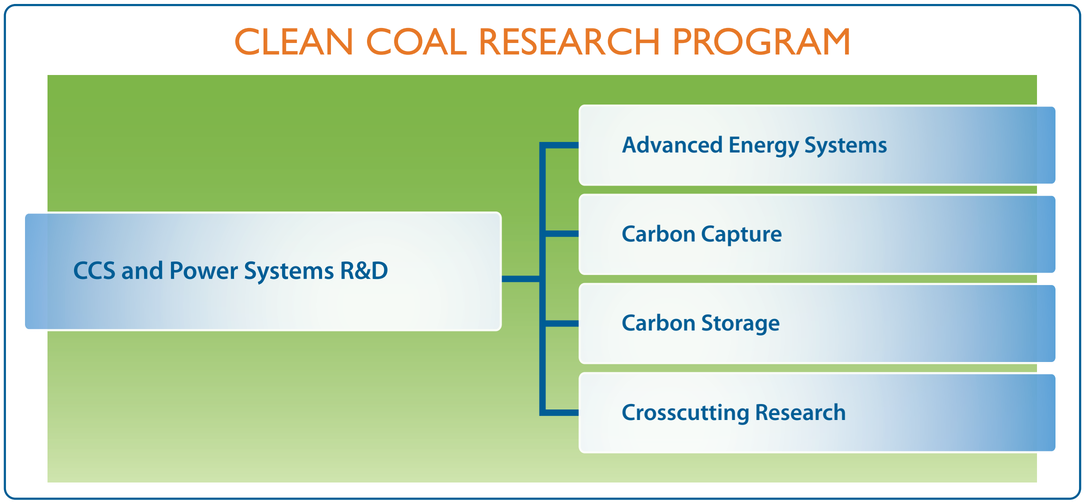


Figure 3. Fossil Energy Clean Coal Research Program FY14 Budget Structure

The 349 selected projects and tasks were then organized under the subprograms noted previously: Advanced Energy Systems, Carbon Capture, Carbon Storage, and Crosscutting Research. This structure provided a standard means for capturing selected projects and graphically showing how they map to a budgeted program area. The Carbon Storage structure is provided as an example in Figure 4.

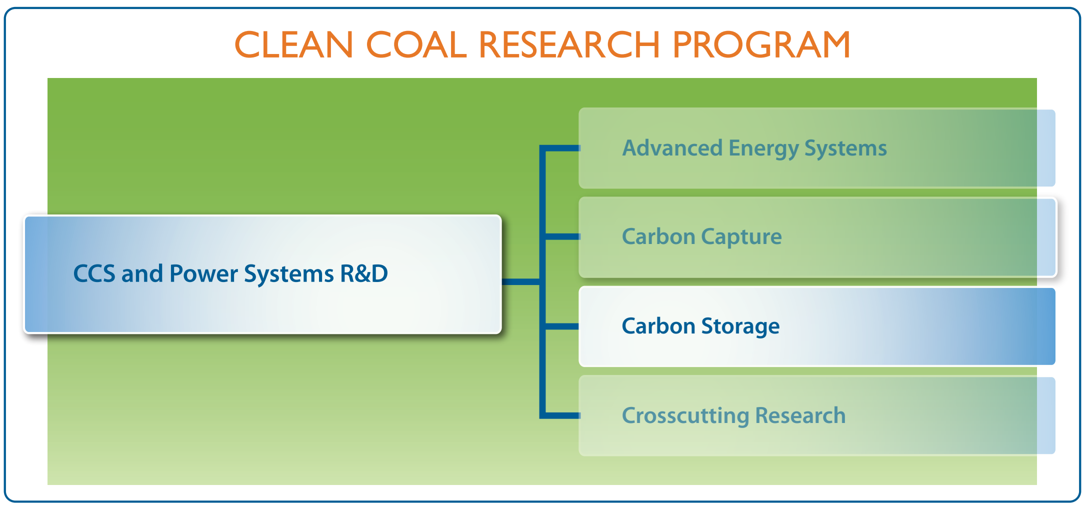


Figure 4. Carbon Storage Component of the Fossil Energy Clean Coal Research Program

The CCRPs four subprograms are divided into Technology Areas and then further subdivided into key technologies. Figure 5 provides an example, identifying Monitoring, Verification, Accounting, and Assessment as one of four Carbon Storage Technology Areas.

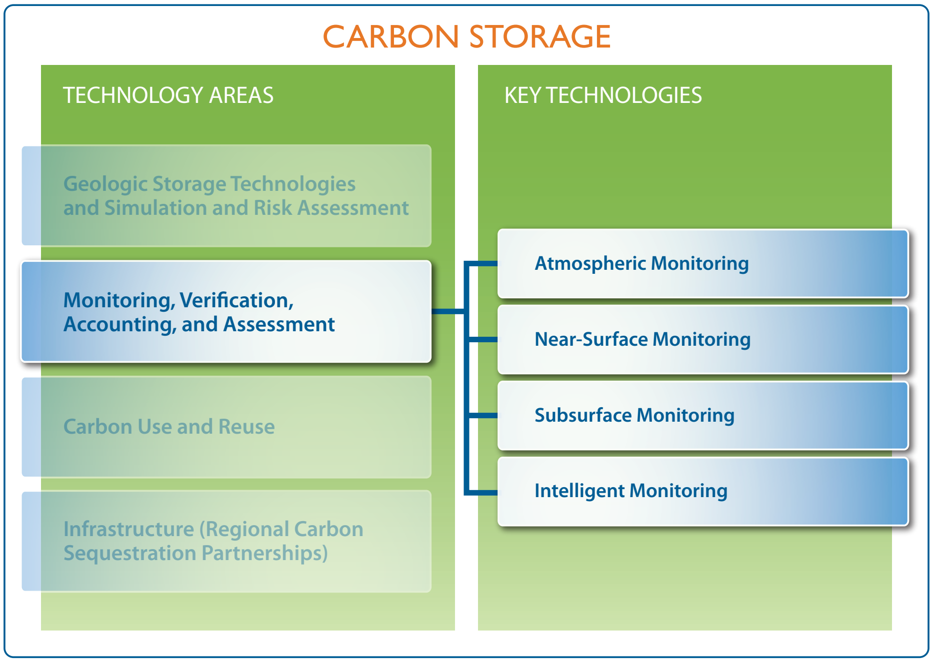


Figure 5. Example of Technology Area and Key Technologies Subdivision

The full portfolio of key technologies is shown in Appendix A. "Key technologies" were associated with each Technology Area, and projects being performed related to those key technologies were assessed to establish an appropriate current state of technology readiness (i.e., TRL score). In addition, a relevancy statement has been developed for each project. Relevancy statements are designed to concisely document the expected contribution to program goals and provide answers to the following key questions:

- What are the project-specific objectives that address the key technology's performance targets (e.g., in the context of contribution to the program's performance goals and measures)?
- What specific technology component is being advanced (as defined in the FY13 Technology Program Plan or other documented reference)?
- How does the project expect to accomplish its targets?

SUMMARY OF RESULTS

R&D SUBPROGRAMS

In summary, 349 active R&D projects and tasks were evaluated and consensus was achieved with the Principal Investigators for all of the ratings. A summary of the TRL ratings by subprogram is provided in Table 3.

Table 3. **CCRP R&D TRL Summary**

R&D Subprogram	Number of R&D Projects						Total
	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	
Advanced Energy Systems	23	43	11	16	2	1	96
Carbon Capture	2	36	9	9	2		58
Carbon Storage	3	50	8	10	7	1	79
Crosscutting Research	31	68	12	4		1	116
TOTAL	**59**	**197**	**40**	**39**	**11**	**3**	**349**

R&D KEY TECHNOLOGIES

The TRA involved the technology review and initial scoring of 349 active R&D projects and tasks within the portfolio of key technologies being advanced by the CCRP. Additionally, consensus was reached for all of the 349 active project ratings. A summary of the TRL ratings as aligned with their respective key technologies is provided in Table 4.

Table 4. **CCRP R&D Key Technologies TRL Summary**

Subprogram	Technology Area	Key Technology	Number of R&D Projects						Total
			TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	
ADVANCED ENERGY SYSTEMS	Advanced Combustion Systems	Oxy-Combustion		2	1		1		4
		Chemical Looping Combustion			2				2
		Advanced Concepts							0
	Gasification Systems	Feed Systems			2	2			4
		Gasifier Optimization and Plant Supporting Systems	2	3				1	6
		Syngas Processing	2	2	3	4			11
	Advanced Turbines	Advanced Combustion Turbines	14	17	1	6	1		39
		Supercritical CO_2 Power Cycles	1	1					2
	Coal and Coal-Biomass to Liquids	Advanced Fuels Synthesis	3	2					5
		Coal-Biomass Feed and Gasification		4	1				5
	Solid Oxide Fuel Cells	Anode-Electrolyte-Cathode (AEC) Development	1	12	1				14
		Atmospheric Pressure Systems				2			2
		Pressurized Systems				2			2
		SUBTOTAL ADVANCED ENERGY SYSTEMS	**23**	**43**	**11**	**16**	**2**	**1**	**96**
CARBON CAPTURE	Pre-Combustion Capture	Solvents	1	1	1				3
		Sorbents				1			1
		Membranes		7					7
	Post-Combustion Capture	Solvents		13	4	2	2		21
		Sorbents	1	10	1	4			16
		Membranes		5	3	2			10
		SUBTOTAL CARBON CAPTURE	**2**	**36**	**9**	**9**	**2**	**0**	**58**
CARBON STORAGE	Geologic Storage Technologies and Simulation and Risk Assessment	Wellbore		4					4
		Mitigation		2	1	1			4
		Fluid Flow, Pressure, and Water Management	2	18	1	1			22
		Geochemical Impacts		7	3				10
		Geomechanical Impacts		1					1
		Risk Assessment		3					3
	Monitoring, Verification, Accounting, and Assessment	Atmospheric Monitoring		3			2		5
		Near-Surface Monitoring		1		2			3
		Subsurface Monitoring	1	8	1	1			11
		Intelligent Monitoring		1					1
	Carbon Use and Reuse	Chemicals		2					2
		Mineralization and Cement			2				2
		Polycarbonate Plastics							0
	Infrastructure (Regional Carbon Sequestration Partnerships)	Clastics and Carbonates				4	4	1	9
		Coal and Organic Shale				1	1		2
		Basalt							0
		SUBTOTAL CARBON STORAGE	**3**	**50**	**8**	**10**	**7**	**1**	**79**
CROSSCUTTING RESEARCH	Crosscutting Research	Sensors and Controls	12	22	2	1		1	38
		Simulation-Based Engineering	2	18	2				22
		High-Performance Materials	17	27	8	2			54
		Environment and Innovative Energy Concepts		1		1			2
		SUBTOTAL CROSSCUTTING RESEARCH	**31**	**68**	**12**	**4**	**0**	**1**	**116**
		TOTAL	**59**	**197**	**40**	**39**	**11**	**3**	**349**

As shown in Figure 1, R&D technologies that achieve a TRL rating of 6 or 7 are strong candidates for advancement into the demonstration program area to continue the process of readying them for potential commercial use. In addition, R&D technologies that achieve a TRL rating of 5 or 6 may be considered for large-scale testing advancement. All four Technology Areas are represented within the 53 technologies spanning the TRL range of 5–7. Of those 53 projects, 19 are associated with Advanced Energy Systems, 11 with Carbon Capture, 18 with Carbon Storage, and 5 with Crosscutting Research. The results of the readiness assessment for these technologies are summarized in Table 5.

Table 5. **Portfolio Summary: Key Technologies with TRL 5–7**

Subprogram	Technology Area	Key Technology	Number of TRL 5–7 Technologies	Technology Assessment Summary
ADVANCED ENERGY SYSTEMS	Advanced Combustion Systems	Oxy-Combustion	1	This project focuses on developing an oxy-combustion system designed for retrofit to tangentially fired, atmospheric-pressure boilers. The impact of this project will be to develop more efficient technologies that lower operating costs. Specifically, this project includes pilot-scale tests on a 5-MWe pilot facility to evaluate impacts of the ratio of oxygen to recycled flue gas, injection of pure oxygen, injection direction, and firing system designs.
	Gasification Systems	Feed Systems	2	Novel dry feed technologies have the potential to significantly improve the efficiency of gasification in two ways: enabling slurry-fed gasifiers to run effectively on low-rank coal, and enabling dry-fed gasifiers to run at high pressure. One project is developing a high-pressure dry feed pump for gasification processes to enable feeding of low-rank coal by developing and testing a pre-commercial-scale prototype pump with a capacity of 400 tons per day and 1,200 psi discharge pressure. A second project focuses on increasing the efficiency and reducing the capital cost of O_2 production through development and demonstration of ion transport membrane (ITM) technology. ITM uses mixed-ion and electron-conducting materials to produce high-temperature/high-purity O_2 at significantly lower capital cost than that of state-of-the-art cryogenic O_2 production systems.
		Gasifier Optimization and Plant Supporting Systems	1	Flame sensors, which are used to monitor gasifier flames in order to determine when maintenance is required on feed injectors, must function in the harsh gasification environment of high temperatures, high pressures, a highly reducing atmosphere, and the presence of ash or slag. Improved flame sensors will enable better control of gasifier operation, potentially leading to increased efficiency and decreased downtime associated with gasifier maintenance. This project focuses on improving flame sensors' design, reliability, and sensitivity.
		Syngas Processing	4	The technologies being developed are focused on high-efficiency processes that operate at moderate to high temperatures and clean syngas of all contaminants to the extremely low levels needed for chemical production. One project will test a two-bed, pressure-swing-adsorption unit on a slipstream of authentic high-hydrogen syngas based on low-rank coal at the National Carbon Capture Center (NCCC). Another project will design and construct a membrane hydrogen-separation unit capable of producing 2 pounds per day of H_2 from syngas derived from coal or coal-biomass. A third project will design, build, and test the high-temperature desulfurization process at pre-commercial scale (50 MWe equivalent) to remove more than 99.9 percent of the sulfur from coal-derived syngas. Another project will develop a new high-hydrogen synthesis gas production technology and demonstrate its techno-economic viability for use in IGCC power plants and coal-to-chemical plants
	Advanced Turbines	Advanced Combustion Turbines	7	The Advanced Turbines Technology Area research effort is developing and supporting a portfolio of technologies that will accelerate turbine performance, efficiency, and cost-effectiveness beyond current state-of-the-art. One project will demonstrate spar-shell airfoil technology to improve options for IGCC airfoil design. The other projects will advance state-of-the-art industrial-frame turbine technology for hydrogen-fueled turbine machinery. Advanced turbine components including hydrogen combustion components, materials, sensors, and airfoil designs under load conditions will be constructed and tested.
	Solid Oxide Fuel Cells	Atmospheric Pressure Systems	2	These projects include fabrication, testing, and post-test analysis of cells, integrating cells into stacks and the development and validation testing of progressively larger stacks to meet performance, reliability, endurance, and cost metrics. One project will confirm improvements through component tests, stack tests, and a thermally self-sustaining system test. Another project will design, fabricate, install, and operate a 50 kWe proof-of-concept solid oxide fuel cell (SOFC) module power plant.
		Pressurized Systems	2	Power systems with pressurized SOFC technology have the potential to achieve efficiencies greater than 60 percent (higher heating value) with greater than 95 percent carbon capture, near-zero emissions, and low water usage. One project will conduct subscale durability tests of single cells, 5-cell and bundle test articles, and a metric stack test. Another project will procure an SOFC stack, install it into a test platform capable of producing air-independent, pressurized operating conditions, and test over a broad spectrum of operating parameters.
SUBTOTAL ADVANCED ENERGY SYSTEMS			**19**	

Table 5. **Portfolio Summary: Key Technologies with TRL 5–7**

Subprogram	Technology Area	Key Technology	Number of TRL 5–7 Technologies	Technology Assessment Summary
CARBON CAPTURE	Pre-Combustion Capture	Sorbents	1	Solid sorbents—including sodium and potassium oxides, zeolites, carbonates, amine-enriched sorbents, and metal organic frameworks (MOFs)—are being explored for pre-combustion CO_2 capture. This project involves designing and fabricating a 0.1-MWe pilot-scale CO_2 separation system and testing on actual syngas at NCCC and at a Sinopec gasification facility.
	Post-Combustion Capture	Solvents	4	Solvent-based CO_2 capture involves chemical or physical absorption of CO_2 from flue gas into a liquid carrier. One project focuses on the development and scaleup of a capture process using a non-aqueous solvent/amine mixture. Another project will design and build a 1-MWe pilot plant and conduct long-term testing to demonstrate solvent stability. A third project will conduct pilot-scale testing of a unique nozzle-based solvent contacting system. Another project will improve energy performance by integrating a flue gas high-efficiency system waste heat recovery technology into a pilot amine-based CO_2 capture process and host pulverized coal unit.
		Sorbents	4	Solid sorbents include sodium and potassium oxides, zeolites, carbonates, amine-enriched sorbents, and MOFs. These technologies range from bench-scale tests and validation in relevant environments to pilot-scale testing using a 1-MW equivalent slipstream at an operating coal-fired power plant. These include technologies being developed and tested at NCCC.
		Membranes	2	Membrane-based CO_2 capture uses permeable or semi-permeable materials that allow for selective transport and separation of CO_2 from flue gas. This technology is being developed at a 1-MW pilot-scale equivalent testing capacity at NCCC.
SUBTOTAL CARBON CAPTURE			**11**	
CARBON STORAGE	Geologic Storage Technologies and Simulation and Risk Assessment	Mitigation	1	Permanent CO_2 storage relies on the presence of a competent geologic seal that will retain the CO_2 for millennia. This project is developing and performing a field test of a microbial biofilm capable of precipitating calcium carbonate ($CaCO_3$) minerals and sealing a small-aperture pathway.
		Fluid Flow, Pressure, and Water Management	1	Carbon dioxide injected into the subsurface will flow through the microscopic and macroscopic pores and fractures that are inherent to storage formations and vary according to the type or rock, depositional environment, and geologic history of the site. This project focuses on developing ways to improve predictions of injectivity and capacity of saline formations and depleted gas reservoirs and on developing innovative, high-resolution methods for monitoring CO_2 in the subsurface.
	Monitoring, Verification, Accounting, and Assessment	Atmospheric Monitoring	2	Atmospheric monitoring techniques include sensors for CO_2 and natural and injected chemical tracers, airborne or satellite gas sensors, eddy covariance, and laser-induced differential absorption radar (LIDAR) techniques. One project is developing and validating a scanning eye-safe diode laser-based DIAL system to determine possible CO_2 leakage to the atmosphere over large areas and for extended periods. Another project is developing a high-precision, low-cost method to detect fossil fuel CO_2 in the atmosphere by modifying and field testing a carbon-14 analyzer.
		Near-Surface Monitoring	2	Near-surface monitoring includes sampling and analysis of soil gas for CO_2, natural chemical tracers or introduced tracers, and geochemical analysis of groundwater samples. One project is developing two systems to inject and tag CO_2 with carbon-14 and measure the radioactivity of collected samples thereby improving the overall monitoring resolution. Another project is improving monitoring capabilities and reducing cost by integrating data from space geodesy, seismology, and geochemistry and assessing the cost and efficacy of these procedures.
		Subsurface Monitoring	1	Subsurface monitoring techniques quantify and track the CO_2 in the reservoir and detect potential movement of the CO_2 out of the injection interval. Subsurface monitoring also provides information on brine pressures and movement, plume stabilization and the long-term behavior of the CO_2 in the reservoir. This project is evaluating CO_2 storage in basalts and validating mineral carbonation through use of tracers, fluid sampling, and core drilling and analyses.
	Infrastructure	Clastics and Carbonates	9	Storage reservoirs collectively referred to as clastics are derived primarily from sand deposited in a variety of depositional environments. These technology efforts are focused on assessing and validating regional clastic reservoirs as a potential CCS option either by preparing for or by current active injection of CO_2 at project end. Carbonate deposits include isolated banks with flat tops and walls that slope steeply down into the ocean (reef), continental shelf deposits, and ramp-like shelves that slope into shallow ocean basins (shallow shelf). These technology development efforts are focused on assessing and validating regional carbonate reservoirs as a CCS option by preparing for eventual injection of CO_2 at project end.
		Coal and Organic Shale	2	In coal, CO_2 is adsorbed into the matrix and locked in place while shale is very fine grained rock with low permeability. This technology development effort is assessing and validating coal/shale as a potential CCS option by preparing for an eventual ECBM injection test at project end.
SUBTOTAL CARBON STORAGE			**18**	

Table 5. **Portfolio Summary: Key Technologies with TRL 5–7**

Subprogram	Technology Area	Key Technology	Number of TRL 5–7 Technologies	Technology Assessment Summary
CROSSCUTTING RESEARCH	Crosscutting Research	Sensors and Controls	2	Novel sensors and advanced process controls are critical and enabling technologies for advanced near-zero-emissions power systems. One project is developing a sensor utilizing a tunable diode laser to measure H_2O, carbon monoxide, CO_2, and methane concentrations inside a high-temperature, high-pressure vessel. Another project is developing a sapphire-based sensor that records temperature data at up to 1,600 °C.
		High-Performance Materials	2	Power-generation plants operate under extreme conditions from a materials standpoint. Future advanced generation facilities will be expected to withstand harsher environments due to higher demands for increased efficiency, quicker plant startups and turndowns, cycling, and alternative power source supplementation. One project is conducting experimentation and computational studies on nickel-base alloys. Another project is developing the materials technology required to operate an ultra-supercritical steam boiler.
		Environment and Innovative Energy Concepts	1	Advanced power-generation concepts such as direct power extraction, novel management and conservation of water, and other innovative ideas have the potential to increase the efficiency and offset the penalty associated with capturing CO_2 from power generation using fossil fuels. This project is developing advanced sorbents for reduction of sulfur from syngas and combustion streams and for recovery of water for power plant use.
SUBTOTAL CROSSCUTTING RESEARCH			**5**	
TOTAL PROJECTS WITH TRL 5–7			**53**	

Due to the dynamic nature of R&D, technologies mature at different rates and become ready for demonstration leading to deployment at different times. Accordingly, two distinct technology maturation pathways have been identified, and both are critical to the successful achievement of program goals:

- **PATHWAY NO. 1—LARGE PILOT-SCALE TESTS LEADING TO FULL-SCALE COMMERCIAL DEMONSTRATION:** A review of the technologies being developed internally under the CCRP and externally by others, both domestically and internationally, identified more than 30 technologies undergoing testing at small scale (0.5–5 MW equivalent) that will require additional testing at a larger scale (10–50 MW equivalent) before they will be ready for full-scale commercial demonstration. Thus, a two-step progression is required to ready these technologies for deployment: (1) large pilot-scale testing followed by (2) full-scale commercial demonstration. In general, to begin this progression, technologies must achieve a TRL rating of 5 or 6.
- **PATHWAY NO. 2—EARLY FULL-SCALE COMMERCIAL DEMONSTRATIONS:** In addition to the technologies described above, several technologies under development internally and externally will be demonstration-ready in the near-term and more will be maturing as the 2020 timeframe approaches. These technologies have undergone pilot-scale testing in the 10–50 MW equivalent range and are ready to be demonstrated at commercial scale (≈100 MW equivalent). Thus, for these technologies, only one step remains prior to their being made ready for deployment: full-scale commercial demonstration. In general, candidate technologies for advancement into the full-scale commercial demonstration program area must achieve a TRL rating of 6 or 7.

As shown in Table 4, 50 CCS and Power Systems R&D technologies received TRL scores of 5 or 6, identifying them as potential candidates for large pilot-scale testing. In addition, 14 technologies received scores of TRL 6 or 7, identifying them as potential candidates for early full-scale commercial demonstration. The 11 projects that received a TRL rating of 6 require additional scrutiny to determine if they should be subject to the two-step Pathway No. 1 rather than to immediate progression to Pathway No. 2.

ACTIVE FULL-SCALE COMMERCIAL DEMONSTRATIONS

DOE is addressing the key challenges that confront the wide-scale industrial deployment of CCS technologies by sponsoring large-scale demonstrations of key R&D technologies including the cost-effective capture, utilization, and storage of CO_2 integrated with power-generation and industrial facilities. The CCS Demonstrations program area consists of three components: CCPI, FutureGen 2.0, and ICCS—cost-shared partnerships between the Government and industry focused on demonstrating advanced coal-based power-generation and industrial technologies at commercial scale. By advancing the development of key CCS technologies, these demonstrations will contribute to the achievement of the President's goal of 83 percent reduction of GHG emissions by 2050 (from a 2005 baseline).

These demonstrations are categorized into four CO_2 capture and storage-related pathways:

- **PRE-COMBUSTION** refers to a process in which a hydrocarbon fuel is gasified to form a synthetic mixture of hydrogen and carbon monoxide. Using shift reactors, the carbon monoxide is converted to CO_2 that is captured from the synthesis gas before it is combusted. The captured CO_2 is then stored and/or utilized.
- **POST-COMBUSTION** refers to capturing CO_2 from the stack gas after a fuel has been combusted in air. The captured CO_2 is then stored and/or utilized.
- **OXY-COMBUSTION** refers to an advanced combustion system whereby a hydrocarbon fuel is combusted in pure or nearly pure oxygen rather than air, producing a mixture of CO_2 and water that can easily be separated to produce pure CO_2, facilitating capture. The captured CO_2 is then stored and/or utilized.
- **INDUSTRIAL CARBON CAPTURE AND STORAGE** refers to the capture of CO_2 from industrial sources that produce a variety of commodities, including power. The captured CO_2 is then stored and/or utilized.

These four demonstration pathways are collectively designed to advance (1) coal-based power-generation technologies (including oxy-combustion) coupled with CCS and (2) technologies that capture and store CO_2 emissions from industrial sources into underground formations, in conjunction with monitoring, verification, accounting (MVA), and assessment protocols to provide a high level of confidence that injected CO_2 remains permanently sequestered in geologic formations.

Today, demonstration of key CCS technologies is being achieved via eight diverse power-generation and industrial platforms. These demonstration platforms represent various technology configurations, utilize a diverse set of feedstocks, produce a variety of commodities, and utilize the captured CO_2 for multiple purposes including chemical production, permanently storing the captured CO_2 in saline reservoirs, or EOR (by others).

These demonstration platforms are composed of multiple technologies, some of which have been demonstrated at significant scale, though in different applications, while others have been operated at pilot scale but with limited continuous operation. Thus, the ongoing focus of the CCS Demonstrations program area is to conduct the requisite engineering design, construction, startup, and operations, including integration with other component technologies, to successfully demonstrate performance in different applications and at different scales.

More information on these active demonstrations and their configurations can be found by visiting the individual Major Demonstration project factsheets (click links below).[12]

SCS-KEMPER	HECA	SUMMIT	PETRA NOVA
FUTUREGEN 2.0	ADM	APCI	LEUCADIA

12 www.netl.doe.gov/research/coal/major-demonstrations/clean-coal-power-initiative/ccpi_285-mw | www.netl.doe.gov/research/coal/major-demonstrations/clean-coal-power-initiative/ccpi-heca | www.netl.doe.gov/research/coal/major-demonstrations/clean-coal-power-initiative/ccpi-summit | www.netl.doe.gov/research/coal/major-demonstrations/clean-coal-power-initiative/ccpi-petra-nova | www.netl.doe.gov/research/coal/major-demonstrations/futuregen | www.netl.doe.gov/research/coal/major-demonstrations/industrial-carbon-capture-and-storage/iccs-archer | www.netl.doe.gov/research/coal/major-demonstrations/industrial-carbon-capture-and-storage/iccs-air | www.netl.doe.gov/research/coal/major-demonstrations/industrial-carbon-capture-and-storage/iccs-leucadia

Benefits

For the past 25 years, DOE has been cofunding large-scale demonstrations of clean coal technologies to hasten their adoption into the commercial marketplace. These demonstrations are the logical extension of the R&D activities performed under the CCRP, and DOE's financial support is needed to help reduce the risks inherent in these first-of-a-kind projects. To date, over 80 projects have been awarded and 41 projects have been successfully completed. DOE's funding commitment has exceeded \$5 billion (ARRA + Base), and its industrial partners have committed an additional \$13 billion.

Public benefits from the CCS Demonstrations include reduced electricity costs resulting from increased power-generation efficiencies, decreased cost of health care resulting from lower pollutant emission rates, increased employment opportunities, and increased tax revenues. These benefits have been estimated to exceed \$100 billion through 2020.[13]

Figure 6 links the Technology Areas to the related development pathways through the CCS Demonstrations program and projects.

CCS DEMONSTRATIONS TECHNOLOGY DEVELOPMENT

			R&D SUBPROGRAMS: Advanced Energy Systems			Carbon Capture	Carbon Storage	
CO_2 CAPTURE AND STORAGE PATHWAY	DEMONSTRATION PROGRAM	PROJECT	TECHNOLOGY AREA: Gasification Systems	Advanced Turbines	Advanced Combustion Systems	Pre- and Post-Combustion Capture	Carbon Use/Reuse and Storage	MVA
Pre-Combustion	CCPI	SCS Kemper	●	●		●	●	
Pre-Combustion	CCPI	HECA	●	●		●	●	●
Pre-Combustion	CCPI	Summit	●	●		●	●	●
Post-Combustion	CCPI	Petra Nova				●	●	●
Oxy-Combustion	FG 2.0	FG 2.0			●	●	●	●
Industrial Carbon Capture and Storage	ICCS	ADM					●	●
Industrial Carbon Capture and Storage	ICCS	Air Products				●	●	●
Industrial Carbon Capture and Storage	ICCS	Leucadia				●	●	●

● - Key Technologies Being Advanced/Demonstrated by CCS Demonstrations Portfolio

Figure 6. CCS Demonstrations Technology Development

13 Bezdek, R. Wendling, R., *The Return on Investment of the Clean Coal Technology Program in the USA*. Energy Policy, Vol. 54, March 2013.

Technology Readiness Assessment

The TRA discipline is a new practice within the CCRP. Since it is the goal of the demonstration program to advance technologies to the point of commercial readiness (i.e., TRL 9), the TRA methodology would be most useful in assessing the status of technologies once the demonstration concludes, thus serving as a tool for aiding future investment decisions that may be needed to advance specific technologies to a condition of commercial readiness.

As a result, an appropriate time to conduct the TRA would be as part of the Post-Project Assessment (PPA) that DOE conducts after the completion of each demonstration. Each PPA provides a concise description of the goals, technologies, and costs; and evaluates the success relative to these factors. Each PPA provides a concise description of the goals, technologies, and costs, and evaluates the success relative to these factors. The PPA typically is completed and issued after DOE receives the final report from the recipient.

The APCI project began full operation of both trains on March 7, 2013, and accomplished a major milestone on April 24, 2014, with the capture and storage of 1 million tonnes of CO_2. In recognition of this milestone, a preliminary TRA assessment was conducted and the results are presented in Table 6. A final TRA will be conducted following project completion as part of the PPA.

Table 6. APCI Project—Preliminary Technology Readiness Assessment

Technologies	TRL Rating
Vacuum Swing Adsorption	8
Gas Turbine	9
HRSG	9
CO_2 Drying/Compression	9
CO_2 Transport	9
MVA Process	9

Systems Readiness Assessment

The integration of unproven and/or first-of-a-kind technologies into new or existing projects can create significant risks to the achievement of the cost, schedule, and performance goals. The degree of integration risk often directly influences the cost, schedule, and performance margins that are applied to specific technologies and projects. This issue is a long-standing challenge in the business of technology development, being formally recognized and discussed in various publications dating back to the 1970s. The complexity associated with integrating multiple technologies into large demonstration platforms has prompted the SCC to assess a specific integration-related tool known as the Systems Readiness Level (SRL) process. The assessment is part of a constant SCC effort to search for ways to improve its assessment of the technology readiness of both individual technologies and demonstration platforms.

Initially developed by DoD, the SRL process responds to a perceived shortfall in the TRA process to adequately represent the complexities associated with the integration of multiple technologies of various TRL ratings into a system configuration. The SRL process maintains the development of TRLs, but adds an evaluation of Integration Readiness Level (IRL) by developing and applying a specific set of criteria related to integration complexity. The IRLs are then determined for all of the significant interfaces between the major equipment. The SRL is then determined by using a mathematical model that multiplies the TRLs by the IRLs and sums to a total score that can be comparatively evaluated to determine overall systems readiness.

There have been numerous proponents of the SRL process as well as a few detractors. Based on a preliminary review of the SRL process, the SCC has determined that there is adequate up-side potential to warrant a more detailed evaluation to determine applicability. Accordingly, an internal steering committee has been formed consisting of the Director, Office of Major Demonstrations and other high-level SCC managers and division directors. Following selection of the appropriate task performance team, which includes NETL personnel and support contractors, work has recently commenced on the development of IRL and SRL scales and criteria, followed by the detailed assessment of two completed projects. The steering committee will then review the results to determine future steps, which may include the assessment of one or more ongoing projects; however, if the process does not provide significant program benefits, it may be abandoned.

Potential applications of the SRL process relate not only to the bi-yearly assessments of new and ongoing projects, but to the entire spectrum of project management, including the development of funding opportunity announcements, project selection criteria, and project performance requirements. However, the evaluation process is in its infancy and the ultimate beneficial applications, if any, are yet to be determined. If proven beneficial for bi-annual TRA reporting of the status of the demonstration platforms, the SRL evaluations would be conducted as part of the PPA process, similar to the TRL evaluation described previously.

demonstration in operation

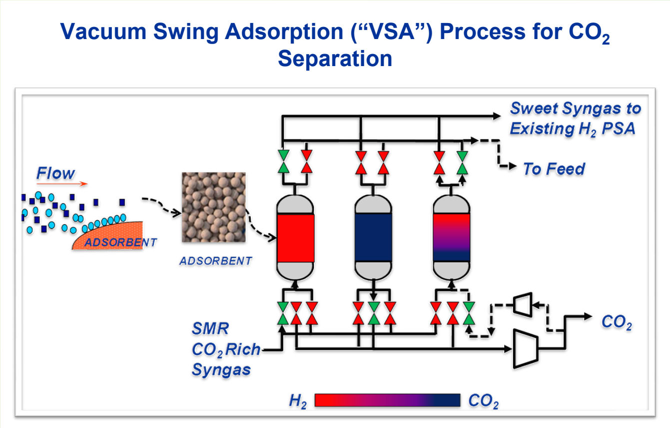
AIR PRODUCTS AND CHEMICALS, INC. | ICCS PROJECT

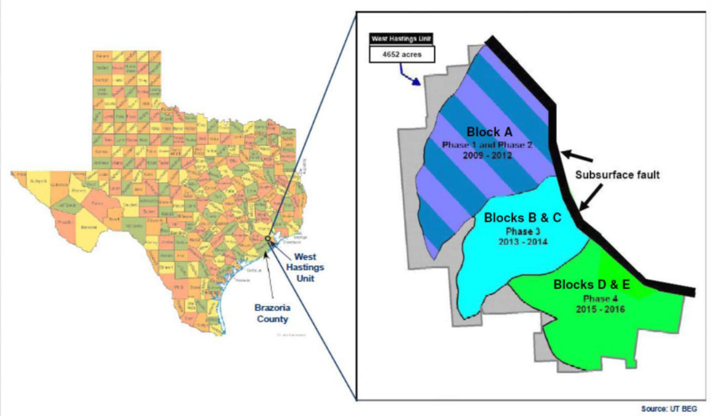
DOE selected Air Products and Chemicals, Inc., to receive ICCS program funding through the American Recovery and Reinvestment Act of 2009, for its project entitled, "Demonstration of CO_2 Capture and Sequestration of Steam Methane Reforming Process Gas Used for Large-Scale Hydrogen Production." For this project, Air Products is demonstrating a state-of-the-art system to concentrate CO_2 from two steam methane reformer (SMR) hydrogen-production plants located in Port Arthur, Texas.

Air Products has retrofitted its two Port Arthur SMRs with a vacuum swing adsorption (VSA) system to separate the CO_2 from the process gas stream, followed by compression and drying processes. This process is designed to concentrate the initial stream containing from 10–20 percent CO_2 to greater than 97 percent CO_2 purity. The compressed CO_2 is then delivered to the Denbury pipeline for transport to Texas EOR projects in the West Hastings Field where an MVA program ensures the injected CO_2 remains in the underground geologic formation. The technology removes more than 90 percent of the CO_2 from the process gas stream used in a world-class-scale hydrogen production facility with negligible impact on the efficiency of hydrogen production.

Construction has been completed and the project is in the Operations Phase. It is currently capturing and sequestering an average of nearly 3,000 short tons per day of CO_2, a rate that will yield over 1,000,000 short tons per year, or approximately 0.925 million metric tonnes per year.

On April 24, 2014, the project achieved a major milestone—capturing and storing 1 million metric tonnes of CO_2.





the ENERGY lab

PROJECT FACTS

Industrial Carbon Capture and Storage (ICCS)

Air Products and Chemicals, Inc.: Demonstration of CO_2 Capture and Sequestration of Steam Methane Reforming Process Gas Used for Large-Scale Hydrogen Production

Background

Carbon dioxide (CO_2) emissions from industrial processes, among other sources, are linked to global climate change. Advancing development of technologies that capture and store or beneficially reuse CO_2 that would otherwise reside in the atmosphere for extended periods is of great importance. Advanced carbon capture, utilization and storage (CCUS) technologies offer significant potential for reducing CO_2 emissions and mitigating global climate change, while minimizing the economic impacts of the solution.

Under the Industrial Carbon Capture and Storage (ICCS) program, the U.S. Department of Energy (DOE) is collaborating with industry in cost sharing arrangements to demonstrate the next generation of technologies that will capture CO_2 emissions from industrial sources and either sequester those emissions or beneficially reuse them. The technologies included in the ICCS program have progressed beyond the research and development stage to a scale that can be readily replicated and deployed into commercial practice within the industry.

Project Description

The DOE selected Air Products and Chemicals, Inc. (Air Products) to receive ICCS program funding through the American Recovery and Reinvestment Act (ARRA) of 2009, for its project entitled "Demonstration of CO_2 Capture and Sequestration of Steam Methane Reforming Process Gas Used for Large-Scale Hydrogen Production". For this project, Air Products will demonstrate a state-of-the-art system to concentrate CO_2 from two steam methane reformer (SMR) hydrogen production plants located in Port Arthur, Texas.

Air Products is retrofitting its two Port Arthur SMRs with a vacuum swing adsorption (VSA) system to separate the CO_2 from the process gas stream, followed by compression and drying processes. This process will concentrate the initial stream containing from 10-20 percent CO_2 to greater than 97 percent CO_2 purity.

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Denbury Onshore, LLC

PROJECT DURATION

Start Date
11/16/2009

End Date
09/30/2015

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U.S. DEPARTMENT OF ENERGY

CONCLUSIONS

Beginning in FY12, NETL examined the TRA methodology, established a standard set of benchmarks, conducted a formal assessment of the R&D component of the CCRP using the TRL evaluation discipline, and reported on the maturity of its key technologies. This focused effort was conducted to identify opportunities to improve planning, performance, and communication efforts within the CCRP. For TRA FY14, NETL assessed the lessons learned from the FY12 effort and made a number of improvements reflected in this report. NETL has begun to translate those lessons into program management practices, technology status assessment and reporting—and value is apparent. The TRA process offers opportunities to enhance planning for and management of the CCRP portfolio. In particular, the efforts to develop a standard set of benchmarks to gauge the maturity level of key technologies will enable the SCC to provide a clearer picture of the current status of technologies being advanced within the CCRP and inform and improve the planning of future research pathways. The relative status of the maturity of the complex set of key technologies currently under development and the likelihood of successfully achieving the CCRP's objectives has been enhanced as a result of this assessment exercise. To continue to extract the benefits from the TRA process, NETL's SCC intends to review the status of the R&D portfolio and to update this report on a biannual basis.

In the interim of formally updated reports and for the purposes of providing current information on Coal and Power Systems R&D projects, NETL has developed the *Research Portfolio Web Map*. The web map includes projects across all Technology Areas, including Advanced Energy Systems, Carbon Capture, Carbon Storage, and Crosscutting Research. Additionally, information on the CCS Demonstrations, GSTR, and GSSC projects can be accessed via the web map.

SCC RESEARCH PORTFOLIO WEB MAP

The SCC Research Portfolio Web Map is an interactive web-based map assembled by NETL to provide its users—and the public—with current SCC project information contained within the CCRP portfolio.

The map is accessible on NETL's external website and includes active project information across all Coal and Power Systems technologies including Advanced Energy Systems, Carbon Capture, Carbon Storage, Crosscutting Research, FutureGen 2.0, Industrial Carbon Capture and Storage, Clean Coal Power Initiative, Geologic Sequestration Training and Research, Geologic Sequestration Site Characterization, and ICCS Research. The project data presented in the map is automatically updated on a nightly basis with select SCC Visual User Environment (VUE) information. Specific project data that can be obtained includes performer name; project title; total award value, as well as the DOE share and performer share; Technology Area in which the project falls; whether or not the project is ARRA-funded; and the city and State where the project is being performed.

Within the SCC Research Portfolio Web Map the user can:

- Hover over a project's general vicinity to obtain project-specific information
- Link to project factsheets
- Select a project by spatial location to obtain project-specific information
- Symbolize projects by general location (flare cluster) or categorized by Technology Area (color coded)
- Turn on and off an interactive legend to view only specific color coded Technology Areas
- Display projects associated with the American Recovery and Reinvestment Act and Congressional District information
- Search for specific projects by keywords in the project title or performer name to obtain project-specific information
- Zoom to a specific project
- Select and zoom to a specific State to obtain a summary of project technologies in that State
- Change base maps and turn off projects categorized by Technology Area to decrease or increase displayed information and specific project visibility

The link to the Research Portfolio Web Map welcome page is located in the left hand column of the Coal Research homepage.

The SCC Research Portfolio Web Map can also be accessed via the following link: www.netl.doe.gov/research/coal/gis

APPENDIX A—PORTFOLIO OF KEY TECHNOLOGIES

CCS AND POWER SYSTEMS
PORTFOLIO OF KEY TECHNOLOGIES

SUBPROGRAM	TECHNOLOGY AREA	KEY TECHNOLOGIES
Advanced Energy Systems	Advanced Combustion Systems	Oxy-Combustion; Chemical Looping Combustion; Advanced Concepts
	Gasification Systems	Feed Systems; Gasifier Optimization and Plant Supporting Systems; Syngas Processing
	Advanced Turbines	Advanced Combustion Turbines; Supercritical CO_2 Power Cycles
	Coal and Coal-Biomass to Liquids	Advanced Fuels Synthesis; Coal-Biomass Feed and Gasification
	Solid Oxide Fuel Cells	AEC Development; Atmospheric Pressure Systems; Pressurized Systems
Carbon Capture	Pre-Combustion Capture; Post-Combustion Capture	Solvents; Sorbents; Membranes
Carbon Storage	Geologic Storage Technologies and Simulation and Risk Assessment	Wellbore; Mitigation; Fluid Flow, Pressure, and Water Management; Geochemical Impacts; Geomechanical Impacts; Risk Assessment
	Monitoring, Verification, Accounting, and Assessment	Atmospheric Monitoring; Near-Surface Monitoring; Subsurface Monitoring; Intelligent Monitoring
	Carbon Use and Reuse	Chemicals; Mineralization and Cement; Polycarbonate Plastics
	Infrastructure (Regional Carbon Sequestration Partnerships)	Clastics and Carbonates; Coal and Organic Shale; Basalt
Crosscutting Research	Crosscutting Research	Sensors and Controls; Simulation-Based Engineering; High-Performance Materials; Environment and Innovative Energy Concepts

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TECHNOLOGY READINESS ASSESSMENT
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