# 2012 TECHNOLOGY READINESS ASSESSMENT —OVERVIEW

CLEAN COAL RESEARCH PROGRAM

United States Department of Energy | Office of Fossil Energy

*Pathway for readying the next generation of affordable clean energy technology*

**—Carbon Capture, Utilization, and Storage (CCUS)**

DECEMBER 2012

# DISCLAIMER

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# ABBREVIATIONS

| | |
|---|---|
| AEC | Anode Electrolyte Cathode |
| CCRP | Clean Coal Research Program |
| CCS | carbon capture and storage |
| CCUS | carbon capture, utilization, and storage |
| $CO_2$ | carbon dioxide |
| DoD | Department of Defense |
| DOE | Department of Energy |
| DOE-FE Guide | DOE-Fossil Energy Technology Readiness Assessment Guide |
| ECBM | enhanced coalbed methane |
| EOR | enhanced oil recovery |
| FE | Office of Fossil Energy |
| $H_2$ | hydrogen |
| MW | megawatt |
| NASA | National Aeronautics and Space Administration |
| NETL | National Energy Technology Laboratory |
| OMB | Office of Management and Budget |
| R&D | research and development |
| R&D | research and development |
| SCC | Strategic Center for Coal |
| scfm | standard cubic feet per minute |
| TRA | Technology Readiness Assessment |
| TRL | Technology Readiness Level |

# INTRODUCTION

Consistent with ongoing efforts to supply policy makers with clear information in a form more amenable for them to gauge the maturity of carbon capture, utilization, and storage (CCUS) technologies, the National Energy Technology Laboratory (NETL) has undertaken an assessment of its "key technologies." The *Department of Energy-Fossil Energy Technology Readiness Assessment Guide* (*DOE-FE Guide*[1]) served as the basis for a comprehensive and formal 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 and development (R&D) efforts being supported by the Office of Fossil Energy's (FE) Clean Coal Research Program (CCRP) using the Technology Readiness Level (TRL) evaluation discipline
- Publicly report the results of the TRL evaluation

As of July 2012, there are over 400 active projects within the CCRP research, development, and demonstration (RD&D) portfolio. This portfolio has a value of approximately $16.3 billion composed of a $5.9 billion DOE share and a $10.4 billion private-sector share. The American Recovery and Reinvestment Act of 2009 provided an additional $3.4 billion for FE RD&D to expand and accelerate the commercial deployment of carbon capture and storage (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 CCUS to meet future energy needs worldwide.

The entire portfolio of R&D projects was reviewed and considered as part of the Technology Readiness Assessment (TRA) process. However, not all of projects in the CCRP's active R&D portfolio were deemed suitable for a formal evaluation, based on the criteria set forth in the *DOE-FE Guide*. Many small projects were excluded based on cost (that is, ones that represent relatively small investments). Also, projects that are focused on only simulations and/or analyses were not generally selected for assessment. Consequently over 90 percent of the total value of the R&D component of the CCRP portfolio was included, and the results of this formal TRA are presented in this overview report.

# BACKGROUND

Today the energy resources that fuel our nation's economy are 83 percent fossil-based, with coal playing a significant role. Of the roughly 100 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. 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.

To meet this challenge, FE's CCRP responds specifically to various policy-related drivers including Presidential initiatives, Secretarial goals, the Energy Policy Act of 2005, and the Recovery Act. In addition, FE's strategies reflect congressional testimony provided by the Department of Energy (DOE) representatives in response to these drivers. Ultimately, the CCRP is responsive to the DOE's 2011 Strategic Plan[2] and the fiscal year 2012 Congressional Budget Request, which provide guidance for all activities within DOE.

### *Presidential Initiatives*

President Obama has 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 has established the following targets:

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

1 United States Department of Energy, Office of Fossil Energy. *DOE-FE Technology Readiness Assessment Guide*—DRAFT. September 2011. Accessed July 2012.

2 United States Department of Energy. *Strategic Plan*. May 2011. Accessed July 2012. http://energy.gov/sites/prod/files/2011_DOE_Strategic_Plan_.pdf

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 greenhouse gas 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 [Environmental Protection Agency] 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 greenhouse gas 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."

### *Secretarial Goals*

In concert with the President's goals, Energy Secretary Chu has identified four distinct DOE-specific goals that generally guide management and technology investments applicable to all of its RD&D programs. The Secretary's first goal—catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies—applies directly to the clean coal technologies portion of the CCRP. In May 2011, DOE issued its Strategic Plan (updated February 13, 2012),[3] which provides additional guidance to the CCRP relative to the implementation of the Presidential Initiatives and Secretarial Priorities.

## RESEARCH STRATEGY

In response to the program drivers, 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's Office of Clean Coal and implemented by NETL, is 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 May 2011 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

The CCRP is responsive to the FE Office of Clean Coal's Strategic Plan, which defines program goals, objectives, and technology roadmaps for coal-related efforts. At a more discrete level, the CCRP complies with Federal assessment mechanisms, including the Government Performance and Results Act and FE's Annual Operating Plan.

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/CCUS 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/CCUS 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

3 United States Department of Energy. *Strategic Plan*. Updated February 13, 2012. Accessed July 2012. http://energy.gov/sites/prod/files/DOE%20Strategic%20Plan_2012%20GPRA%20Addendum.PDF

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/CCUS 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: CCUS and Power Systems R&D and CCS/CCUS Demonstrations. Under the CCUS and Power Systems R&D program area, the SCC conducts coal-related research in four subprograms:

- *Carbon Capture* develops technologies to lower the costs of carbon capture from both pre- 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.
- *Advanced Energy Systems* focuses on developing advanced combustion systems, advanced gasification systems, stationary power fuel cells, advanced fuels, and improved gas turbines for future coal-based combined-cycle plants that are cleaner, more efficient, and capture 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 major Technology Areas and each Technology Area—which consists of multiple projects—is organized to pursue the development of key technologies. The flow of technology development that is employed by the CCRP to accomplish its mission to develop technology and ready it for potential commercial deployment is 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 CCUS and Power Systems R&D program area.

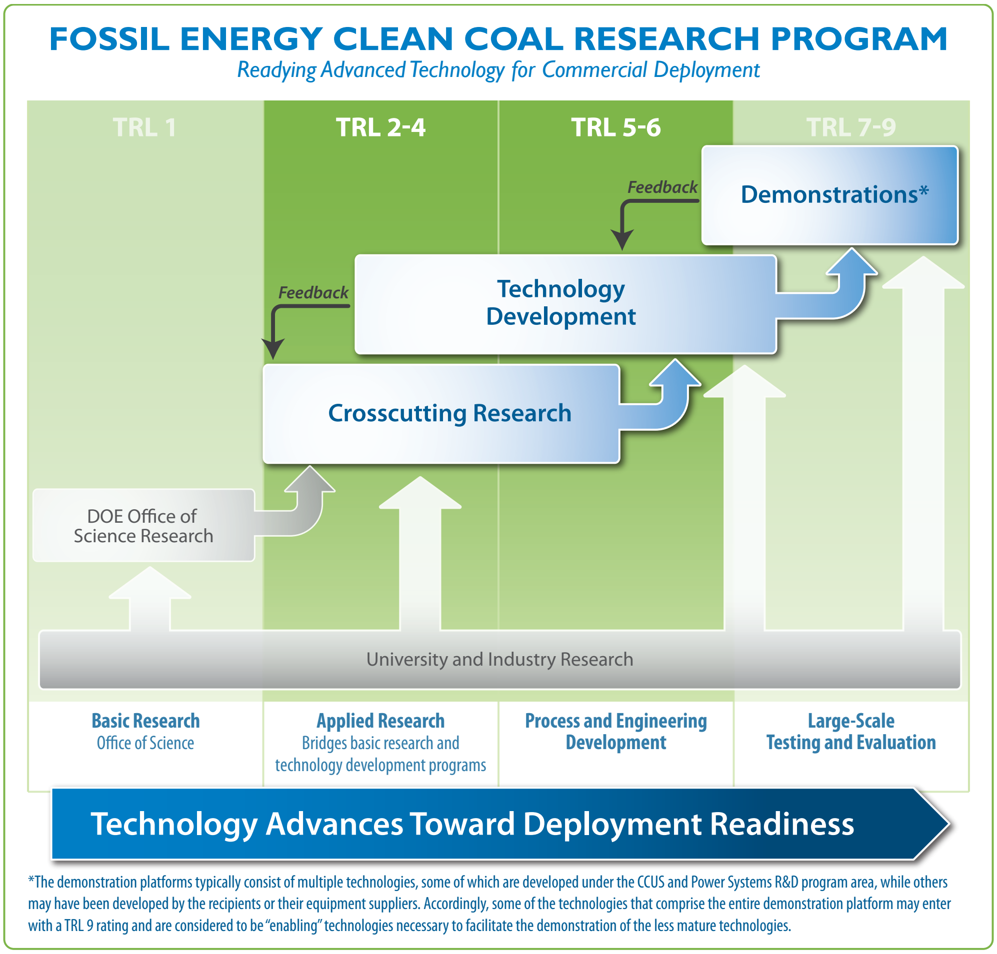



Figure 1: CCRP—Flow of Technology Advancement

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/CCUS 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 CCUS and Power Systems program area; however, an overview of the TRA approach to technologies in the CCS/CCUS Demonstration program area is included for completeness.

# TECHNOLOGY READINESS ASSESSMENT

Although NETL has not previously conducted TRAs of the technologies in its research portfolio, the organization 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, presented on page 11, 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."[4] 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*[5] 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* 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 CCUS.

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, subject matter experts, and individuals knowledgeable in the execution of TRAs[6] carried out the process in a manner that considered the entire spectrum of projects in the R&D portion of the FE CCRP.

The portfolio of ongoing R&D was assembled along key technology lines and reviewed to determine suitability for a formal evaluation and scoring according to the criteria established in the *DOE-FE Guide*. Of the over 400 active projects, 285 met the criteria for conducting a formal TRA. In addition, 34 projects under the University Training and Research Technology Area of the Crosscutting Research subprogram were deemed significant enough to receive a "tabletop review" by the NETL Technology Manager. The University Training and Research projects are funded at less than $300,000 each and therefore fall under the threshold for TRL assessment. However, because considerable research is underway to improve sensors and controls, computational modeling, and high-performance materials, the technology readiness for this Technology Area as a whole was assessed.

The core TRA Team was expanded to include individuals with project-specific knowledge and divided into nine Key Technology Assessment Teams. This approach helped ensure consistency and standardization while also supporting a reasonable timeframe for completion of the effort. Each Key Technology Assessment Team had a full complement of individuals with project

4 Mankins, J., Technology Readiness Level White Paper. 1995, rev. 2004. Accessed June 2012. http://www.artemisinnovation.com/images/TRL_White_Paper_2004-Edited.pdf

5 United States Department of Energy. *DOE Technology Readiness Assessment Guide*. DOE G 413.3-4A. September 15, 2011. Accessed June 2012. https://www.directives.doe.gov/directives/0413.3-EGuide-04a/view

6 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.

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, 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 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 following information: project overview, project and technology status, key contact information, justification statement, and the assessed TRL. The project summaries document the results and establish the basis for completing the final step, which was stakeholder feedback. The *DOE-FE Guide* defines stakeholders as the DOE-FE Program Manager, NETL Technology Manager, TRA assessor, and Industry or University Principal Investigator.

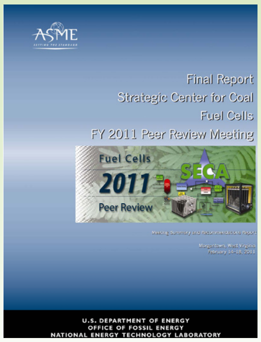
Consensus meetings were held with the NETL Technology Managers for each selected key technology in their purview. Project summaries were changed as necessary to reflect the results of the consensus process.

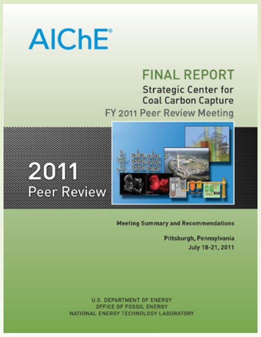
Final project summaries were distributed to the applicable Principal Investigators with a request for feedback and concurrence. In general the feedback was both responsive and timely and, in all but a few cases, confirmed the NETL-assigned TRLs. Based on emerging results that were not known to NETL assessors at the time of NETL's analysis, in a few cases Principal Investigators proposed an increase of one position in the TRL scale.

## PEER REVIEWS—ASSESS CLEAN COAL RESEARCH PROGRAM TECHNOLOGIES

While the 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 President's Management Agenda, 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, American Institute of Chemical Engineers, and the International Energy Agency 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 and action items 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. More information can be found at: http://www.netl.doe.gov/technologies/coalpower/peer-review/index.html

> "Running rigorous evaluations takes money, but investments in rigorous evaluations are a drop in the bucket relative to the dollars at risk of being poorly spent when we fail to learn what works and what doesn't."
>
> Jeffrey Zients, OMB Acting Director, August 2, 2010



The nature of the CCUS and Power Systems R&D portion of the CCRP is to pursue research at the lower and mid-level range of the readiness scale. As such it is common for a project to be focused on a single "key technology." The goal of the assessment effort is to identify the current state of readiness of the key technologies being pursued across the R&D portion of the CCRP. The detailed technology assessment and scoring followed the process depicted in Figure 2.

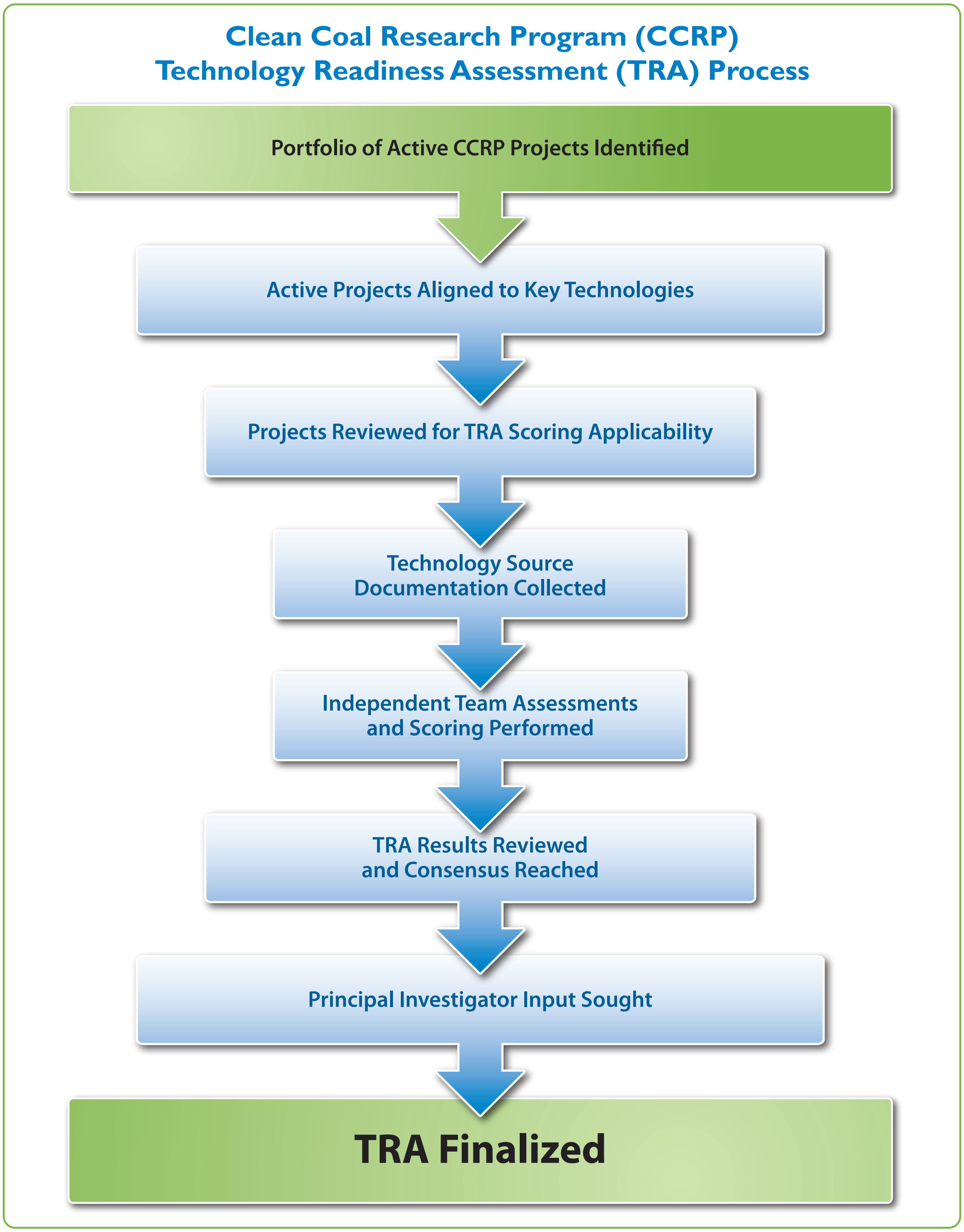



Figure 2: Process Flow for Conducting TRA

# 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*, the *DOE-FE Guide* 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 the 2012 TRA. 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 that separate TRL readiness terminology and scales be developed to guide the assessment. 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.

**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% 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% 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% 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% 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/CCUS 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/CCUS 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). |

**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 operating conditions. 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 life cycle 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[7] 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 life cycle 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 life cycle 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 life cycle of the storage project, including site characterization, injection, and post-injection monitoring and closure. |

## TRA IMPLEMENTATION

NETL's TRA process focuses on "key technologies" and is organized consistent with the budget structure approved via the FY 2012 congressional budget appropriations. The CCRP is thus subdivided into four distinct areas: Carbon Capture, Carbon Storage, Advanced Energy Systems, and Crosscutting Research, as depicted in Figure 3.

7 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.

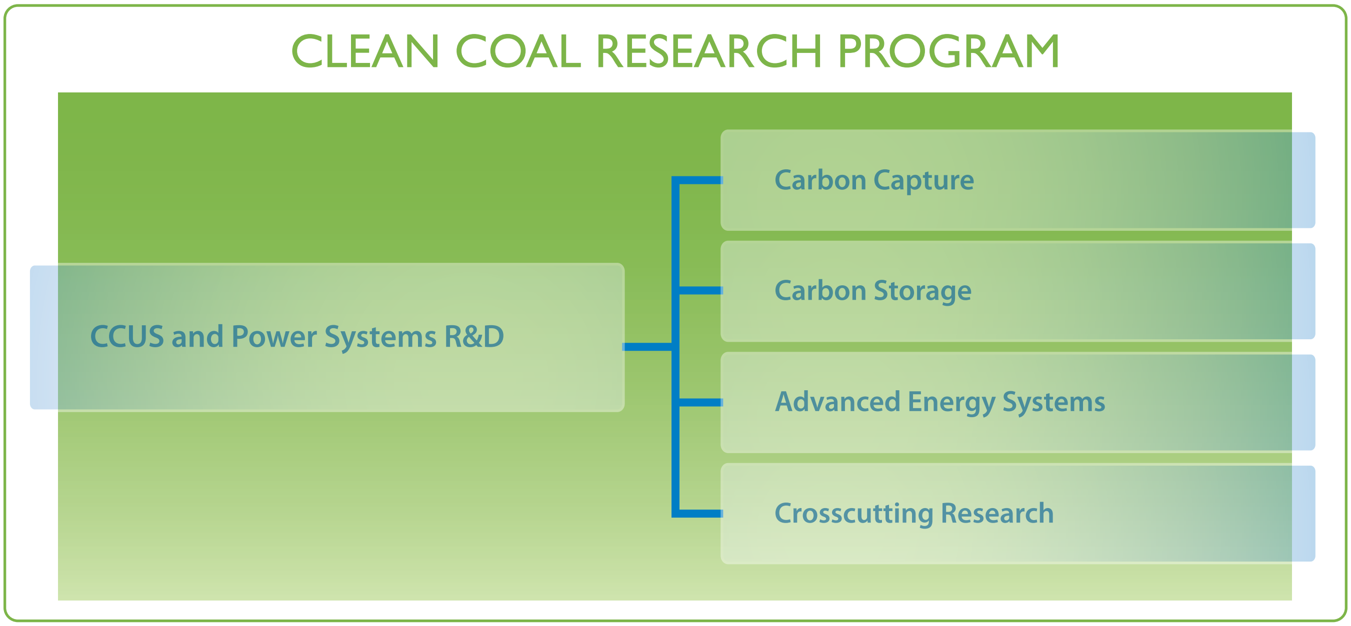



Figure 3: Fossil Energy Clean Coal Research Program FY 2012 Budget Structure

The entire CCUS and Power Systems R&D portfolio was examined to identify projects and individual key technologies that were deemed to warrant a formal TRL evaluation. A two-stage screening process was applied. First, project costs and DOE investment potential were reviewed according to the criteria defined in Table 1 of the *DOE-FE Guide* (see Table 3 below).

**Table 3: TRA Technology Risk-Related Selection Criteria**

| |
|---|
| Do limitations in the understanding of the technology result in significant performance risk (i.e., guarantees related to output, heat rate, availability, environmental performance, including emissions, effluents, noise, etc.)? |
| Do limitations in the understanding of the technology result in a potential cost risk; i.e., the technology may induce significant cost overruns? |
| Do limitations in the understanding of the technology result in a potential schedule risk; i.e., the technology may not be ready for integration into a full-scale demonstration when required? |
| Do limitations in the understanding of the technology impact the safety-related risk of the design? |
| Are there uncertainties in the definition of the end-state requirements (design specification, final operating environment, etc.) for this technology? |

Then the TRL selection criteria, as defined in Table 2 of the *DOE-FE Guide*, and shown in Table 4 below, were assessed for each project. As a result of this process, many small projects were excluded based on cost (that is, ones that represent relatively small investments). Also, projects that are focused on only simulations and/or analyses were not generally selected for assessment. The projects that were assessed all involved the development, demonstration, integration, or modification of technologies deemed to be key to attaining FE's mission.

**Table 4: TRA Technology-Related Selection Criteria**

| |
|---|
| Is the technology new or novel? |
| Does the technology represent a significant modification to an existing process? |
| Does the technology include potentially hazardous features (operational or environmental risk) that require further evaluation? |
| Has the technology been repackaged so a new relevant operating environment is realized? |
| Is the technology expected to operate in an environment and/or achieve performance beyond its original design intention or demonstrated capability? |

The selected projects were organized by the areas noted above: Carbon Capture, Carbon Storage, Advanced Energy Systems, 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.

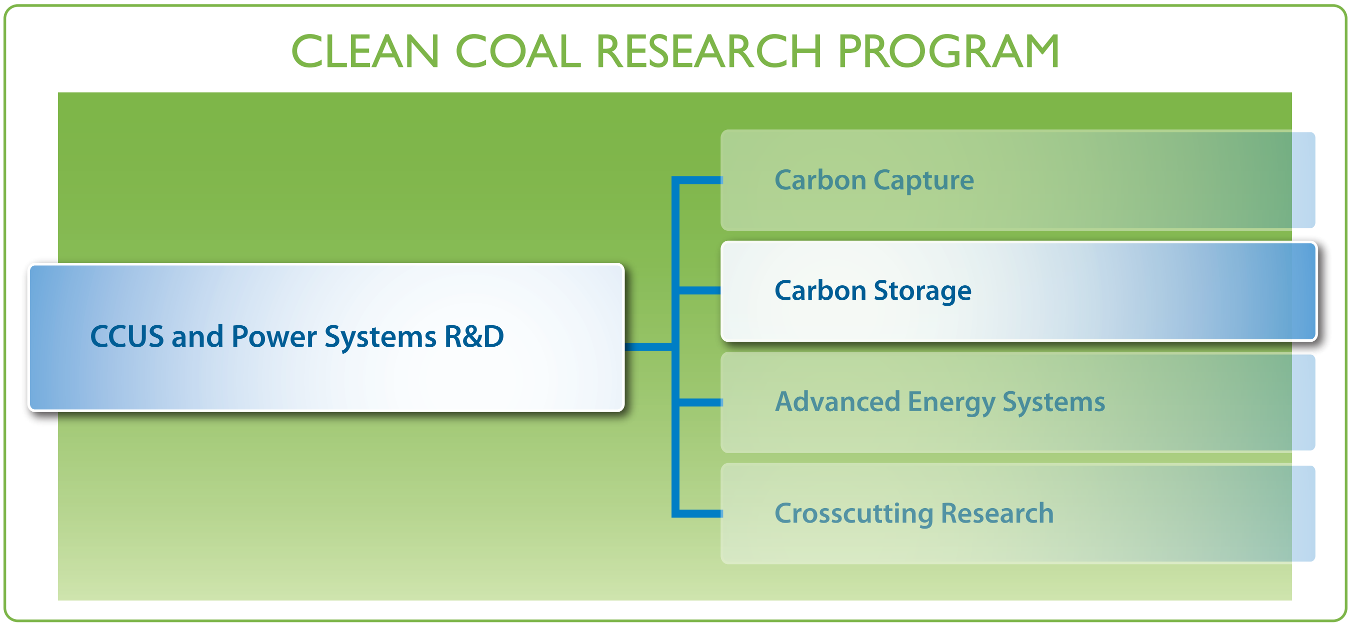



Figure 4: Carbon Storage Component of the Fossil Energy Clean Coal Research Program

The CCRP is divided into Technology Areas. Figure 5 provides an example, showing that Monitoring, Verification, Accounting, and Assessment is one of four Carbon Storage Technology Areas. "Key technologies," such as the four shown for Monitoring, Verification, Accounting, and Assessment in Figure 5, 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 that concisely documents the expected contribution to program goals. These statements contain project objectives, the reason the project objectives are important to achieving program goals, and the research approach being taken to accomplish project objectives.

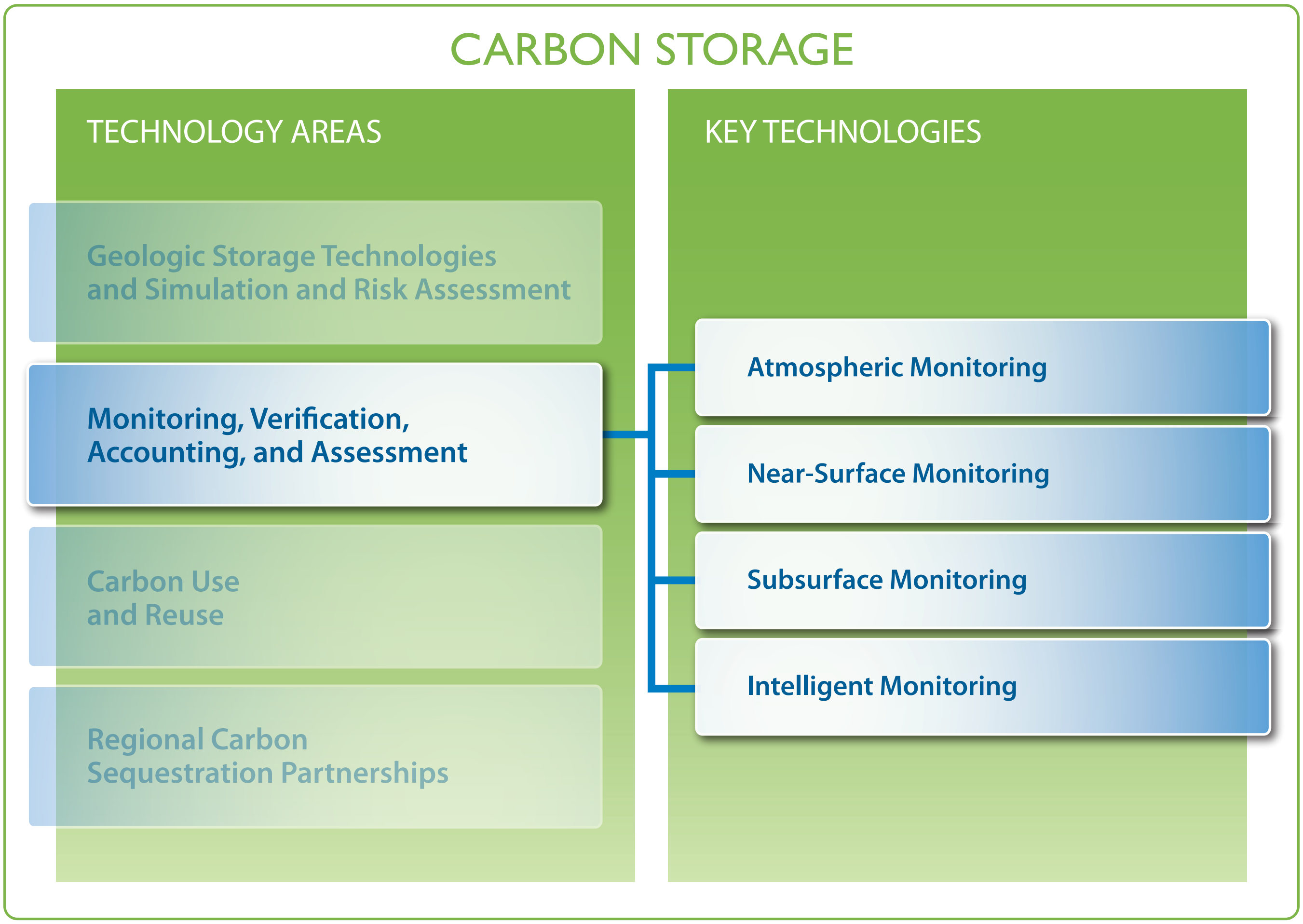



Figure 5: Example of Technology Area and Key Technologies Subdivision

The nature of he CCUS and Power Systems R&D portion of the CCRP is to pursue research at the lower- and mid-level ranges of the readiness scale. As such, it is common for a project to be focused on a single "key technology." The goal of the TRA effort is to identify the current state of readiness of all of the key technologies being developed under the CCUS and Power Systems R&D program area. The detailed technology assessment and associated scoring followed the process depicted in *Figure 2: Process Flow for Conducting TRA* shown on page 12 of this overview report.

# SUMMARY OF R&D RESULTS

## CCUS AND POWER SYSTEMS R&D TECHNOLOGIES

The TRA involved the technology review and initial scoring of 285 active R&D projects within the portfolio of key technologies being advanced by the CCRP (34 additional University Training and Research projects received a "tabletop review"). Additionally, consensus was established for all of the 285 active project ratings. Table 5 summarizes the TRL ratings as aligned with their respective key technologies.

### Table 5: CCRP R&D Key Technologies TRL Summary

| CCUS and Power Systems R&D | Technology Area | Key Technology | Number of R&D Projects | | | | | Total |
|---|---|---|---|---|---|---|---|---|
| | | | TRL 1 | TRL 2 | TRL 3–4 | TRL 5–6 | TRL 7–9 | |
| Carbon Capture | Post-Combustion Capture | Solvents | | 2 | 14 | 2 | | 18 |
| | | Sorbents | | 1 | 8 | 4 | | 13 |
| | | Membranes | | 2 | 8 | 1 | | 11 |
| | Pre-Combustion Capture | Solvents | | 1 | 1 | | | 2 |
| | | Sorbents | | 1 | 3 | | | 4 |
| | | Membranes | | 1 | 5 | | | 6 |
| | | **Subtotal Carbon Capture** | **0** | **8** | **39** | **7** | **0** | **54** |
| Carbon Storage | Geologic Storage Technologies and Simulation and Risk Assessment | Wellbore | | | 1 | | | 1 |
| | | Mitigation | | | 2 | | | 2 |
| | | Fluid Flow, Pressure, and Water Management | | | 14 | 1 | | 15 |
| | | Geochemical Impacts | | | 5 | | | 5 |
| | | Geomechanical Impacts | | | 9 | | | 9 |
| | | Risk Assessment | | | 3 | | | 3 |
| | Monitoring, Verification, Accounting, and Assessment | Atmospheric Monitoring | | | | 2 | | 2 |
| | | Near-Surface Monitoring | | | 1 | 2 | | 3 |
| | | Subsurface Monitoring | | | 11 | | | 11 |
| | | Intelligent Monitoring | | | 2 | | | 2 |
| | Carbon Use and Reuse | Chemicals | | | 4 | | | 4 |
| | | Mineralization/Cement | | | 2 | | | 2 |
| | | Polycarbonate Plastics | | | 1 | | | 1 |
| | Regional Carbon Sequestration Partnerships | Clastics (deltaic, fluvial deltaic, fluvial/alluvial, strandplain, turbidite, eolian, and shelf clastic) | | | 1 | 6 | 1 | 8 |
| | | Carbonates (shallow shelf and reef) | | | | 3 | | 3 |
| | | Coal and Shale | | | | 1 | | 1 |
| | | **Subtotal Carbon Storage** | **0** | **0** | **56** | **15** | **1** | **72** |
| Advanced Energy Systems | Advanced Combustion Systems | Oxy-Combustion | | | 5 | 2 | | 7 |
| | | Chemical Looping | | | 2 | 1 | | 3 |
| | | Advanced Materials | | | 11 | 1 | | 12 |
| | Gasification Systems | Feed Systems | | | 3 | | | 3 |
| | | Gasifier Optimization and Plant Supporting Systems | | 1 | 5 | 1 | | 7 |
| | | Syngas Optimization Systems | | 1 | 4 | | | 5 |
| | Hydrogen Turbines | $H_2$ Turbines | | | | 2 | | 2 |
| | | Oxy-Fuel Turbines for EOR and Power | | | 1 | | | 1 |
| | | Combustion Systems | | | 6 | 0 | | 6 |
| | | Materials and Material Architectures | | | 6 | | | 6 |
| | | Aerodynamics and Heat Transfer | | | 7 | | | 7 |
| | Coal and Coal-Biomass to Liquids (Fuels) | Advanced $H_2$ Membranes | | 2 | 11 | | | 13 |
| | | Coal-Biomass to Liquids | | 1 | 15 | | | 16 |
| | Solid Oxide Fuel Cells | Anode Electrolyte Cathode (AEC) Development | | | 10 | | | 10 |
| | | Atmospheric Pressure Systems | | | 2 | | | 2 |
| | | Pressurized Systems | | | 1 | | | 1 |
| | | Alternative AEC Development | | | 3 | | | 3 |
| | | **Subtotal Advanced Energy Systems** | **0** | **5** | **92** | **7** | **0** | **104** |

**Table 5: CCRP R&D Key Technologies TRL Summary**

| CCUS and Power Systems R&D | Technology Area | Key Technology | Number of R&D Projects | | | | | Total |
|---|---|---|---|---|---|---|---|---|
| | | | TRL 1 | TRL 2 | TRL 3–4 | TRL 5–6 | TRL 7–9 | |
| Crosscutting Research | Plant Optimization Technologies | Sensors and Controls | | 3 | 11 | 6 | 0 | 20 |
| | | Water-Emissions Management and Controls | | | 1 | 4 | | 5 |
| | | Dynamic Systems Modeling | | 2 | 1 | 1 | | 4 |
| | | High-Performance Materials and Modeling | | 1 | 5 | | | 6 |
| | Coal Utilization Sciences | Dynamic Systems Modeling | | 1 | 7 | | | 8 |
| | | Carbon Capture Simulation | | | 1 | | | 1 |
| | | Carbon Storage Risk Assessment | | | 2 | 1 | | 3 |
| | | Innovative Energy Concepts | | 2 | 5 | | | 7 |
| | | High-Performance Materials and Modeling | | | 1 | | | 1 |
| | | **Subtotal Crosscutting Research** | **0** | **9** | **34** | **12** | **0** | **55** |
| | | **Total** | **0** | **22** | **221** | **41** | **1** | **285** |

A summary of the TRL ratings by subprogram is provided in Table 6.

**Table 6: CCRP R&D TRL Summary**

| R&D Subprogram | Number of R&D Projects | | | | | Total |
|---|---|---|---|---|---|---|
| | TRL 1 | TRL 2 | TRL 3–4 | TRL 5–6 | TRL 7–9 | |
| Carbon Capture | 0 | 8 | 39 | 7 | 0 | 54 |
| Carbon Storage | 0 | 0 | 56 | 15 | 1 | 72 |
| Advanced Energy Systems | 0 | 5 | 92 | 7 | 0 | 104 |
| Crosscutting Research | 0 | 9 | 34 | 12 | 0 | 55 |
| **Total** | **0** | **22** | **221** | **41** | **1** | **285** |

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 may be considered for large-scale testing advancement. Of the 42 technologies spanning the CCRP that are at a TRL of 5–7, 23 are associated with Carbon Capture and Carbon Storage. In Post-Combustion Capture, there are a total of seven technologies in the TRL 5–6 range. Carbon Storage has 16 individual technologies that span three Technology Areas that have matured to the TRL of 5–7. The results of the readiness assessment for these technologies are summarized in Table 7.

**Table 7: Carbon Capture and Carbon Storage TRL 5–7 Portfolio Summary**

| CCUS R&D | Technology Area | Key Technology | Number of TRL 5–7 Technologies | Technology Assessment Summary |
|---|---|---|---|---|
| Carbon Capture | Post-Combustion Capture | Solvents | 2 | Solvent-based $CO_2$ capture involves chemical or physical absorption of $CO_2$ from flue gas into a liquid carrier. One of these technologies is integrating waste heat recovery into an existing 25-MW pilot amine-based $CO_2$ capture process and the other is designing, building, and operating a 1-MW equivalent pilot plant. |
| | | 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 at the National Carbon Capture Center. |
| | | Membranes | 1 | 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 the National Carbon Capture Center. |
| | | **Subtotal Carbon Capture** | **7** | |

**Table 7: Carbon Capture and Carbon Storage TRL 5–7 Portfolio Summary**

| CCUS R&D | Technology Area | Key Technology | Number of TRL 5–7 Technologies | Technology Assessment Summary |
|---|---|---|---|---|
| Carbon Storage | Geologic Storage Technologies and Simulation and Risk Assessment | Fluid Flow, Pressure, and Water Management | 1 | Computer simulations of $CO_2$ flow and pressure increases are used to design injection operations. This technology development effort is providing an understanding of the enhancement of coal-bed methane production and geologic injection limitations to achieve safe, commercial geologic $CO_2$ storage by actively injecting $CO_2$ and recovering methane and then developing models and analyses on reservoir effects. |
| | Monitoring, Verification, Accounting, and Assessment | Atmospheric Monitoring | 2 | Atmospheric $CO_2$ monitoring provides assurance that there are no leaks of stored $CO_2$ to the atmosphere. These technologies are developing field-deployed remote and noninvasive monitoring tools to quantify $CO_2$ storage and leakage and developing and validating a scanning eye-safe diode laser-based Differential Absorption Lidar under in-situ conditions. |
| | | 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. These technologies are focused on in-field, continuous, non-invasive soil carbon canning system and verification and accounting of carbon sequestration using a field ready 14C isotopic analyzer. |
| | Regional Carbon Sequestration Partnerships | Clastics | 7 | Storage reservoirs collectively referred to as clastics are derived primarily from sand deposited in a variety of depositional environments. These technology focused efforts are focused on assessing and validating regional clastic reservoirs as a potential CCUS option either by preparing for or by current active injection of $CO_2$ at project end. |
| | | Carbonates | 3 | Carbonate deposits include isolated banks with flat tops and walls that slope steeply down into the ocean (reef), and continental shelf deposits, and ramp-like shelves that slope into shallow ocean basins (shallow shelf). These three technology development efforts are focused on assessing and validating regional carbonate reservoirs as a CCUS option by preparing for eventual injection of $CO_2$ at project end. |
| | | Coal and Shale | 1 | 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 CCUS option by preparing for an eventual ECBM injection test at project end. |
| | | **Subtotal Carbon Storage** | **16** | |

In a similar fashion, Advanced Energy Systems and Crosscutting Research have developed a number of key technologies that have achieved a TRL of 5–6 and are well positioned for large-scale testing. Additionally, a large number of technologies in Advanced Energy Systems were assessed at TRL 4 yet are recognized to be rapidly advancing toward TRL 5–6. These technologies are further discussed in the detailed assessment results sections of this overview report.

# CCS/CCUS DEMONSTRATIONS

Advanced technologies developed in the CCRP need to be tested at full scale in an integrated facility before they can be considered ready for commercial deployment. To achieve success in the marketplace, technical, environmental, and financial challenges associated with the deployment of new advanced coal technologies must be overcome. Commercial-scale demonstrations help industry to understand and overcome component integration and startup performance issues. By reducing the risk profile associated with new and often first-of-a-kind technologies, the opportunity for private financing and investment for subsequent plants is greatly improved.

DOE is addressing the key challenges that confront the wide-scale industrial deployment of CCS/CCUS 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. 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.

Today, demonstration of key CCS/CCUS 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).

Via the CCS/CCUS Demonstrations, FE is supporting the development and demonstration of a range of advanced coal-based power-generation technologies in six Technology Areas:

- Gasification Systems
- Advanced Turbines
- Advanced Combustion Systems
- Pre-Combustion Capture and Post-Combustion Capture
- Carbon Use/Reuse and Storage
- Monitoring, Verification, Accounting, and Assessment

Figure 6 presents the key technologies being advanced through each Technology Area.

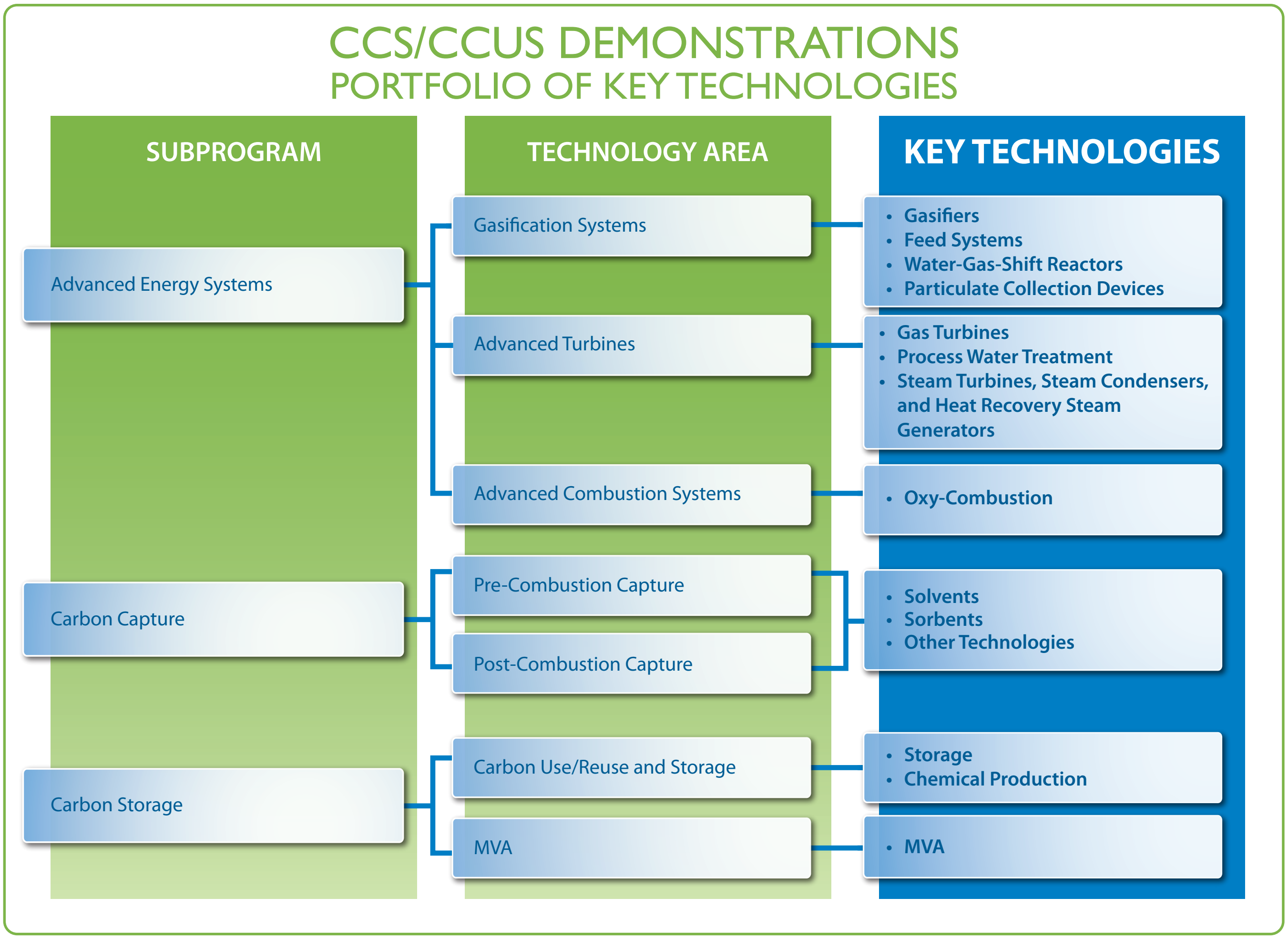



Figure 6: CCS/CCUS Demonstrations Portfolio of Key Technologies

FE's CCUS and Power Systems R&D program area develops individual technologies to the point of demonstration readiness. In general, this corresponds to technology rating levels from TRL 5 to TRL 7. The CCS/CCUS Demonstrations program area is intended to advance technologies to the point of achieving commercial readiness status. Thus, the demonstrations are intended to validate the performance of these technologies and advance them to a higher readiness level (TRL 7 and above). Ultimately, the program goal is to advance these technologies to a rating of TRL 9—*actual system operated over the full range of expected conditions*—but this may not be achievable under a single demonstration platform.

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 that DOE conducts after the completion of each demonstration. Each Post Project Assessment provides a concise description of the goals, technologies, and costs, and evaluates the success relative to these factors. The Post Project Assessment typically is completed and issued after DOE receives the final report from the recipient. Accordingly, the TRA was only completed for the CCUS and Power Systems R&D portion of the CCRP.

# CONCLUSIONS

In the CCUS and Power Systems R&D program area, 42 technologies have been identified as strong candidates for advancement into the CCS/CCUS Demonstrations program area to continue their development for potential commercial use, or they are at a level of technology readiness to be considered for advanced large-scale testing. The breakdown of these advanced key technologies is as follows: Post-Combustion Capture (7), Carbon Storage (16), Advanced Energy Systems (7), and Crosscutting Research (12).

NETL has 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 in the CCRP. NETL is assessing the lessons learned from this endeavor and beginning to translate those lessons into program management practices, technology status assessment, and reporting, and value is already 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 provide an updated status report on a biannual basis.

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