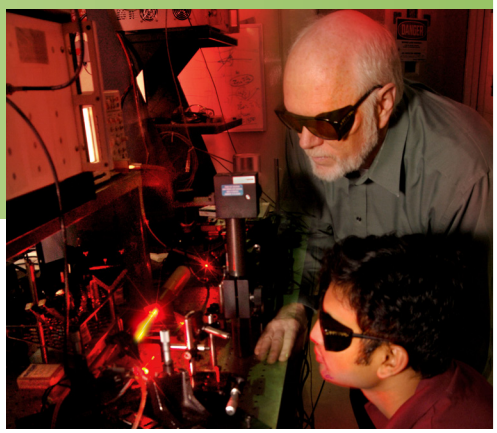
DOE/NETL-2015/1710

2014 TECHNOLOGY READINESS ASSESSMENT

—A CHECKPOINT ALONG A CHALLENGING JOURNEY

JANUARY 2015



CLEAN COAL RESEARCH PROGRAM

United States Department of Energy | Office of Fossil Energy

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EXECUTIVE SUMMARY

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 public issue of the FY12 TRA report presented the results of the first comprehensive assessment of the status of FE's RD&D portfolio. At the conclusion of the FY12 report, a commitment was made to review the evaluation process and to make improvements based on lessons learned. Accordingly, NETL formed a steering committee to consider modifications to enhance the project selection and scoring methodology. As a result of this review, several improvements were incorporated in the FY14 assessment, including:

- The project selection process was modified to eliminate the project cost threshold. As a result, a larger percentage of projects in the research and development (R&D) portfolio were evaluated and scored. For the FY12 report, approximately 70 percent of the portfolio met the selection criteria and were scored. For FY14, this percentage increased to over 80 percent.
- The scoring methodology for field work proposals (FWPs) was improved. In general, the FY12 TRA associated each FWP with one key technology. For FY14, scrutiny of the FWPs at the task level revealed contributions to multiple key technologies leading to a more comprehensive evaluation. The only exception was related to support FWPs, which were not scored because they did not directly contribute to technology advancement.
- Additionally, university research projects have been incorporated into the Crosscutting Research key technologies; as a result, the scoring methodology for university projects was also improved. In FY12, these projects were either not reviewed or received a "tabletop" review. In FY14, these projects were subjected to the same review criteria as all other reviewed projects.

These improvements led to a broader assessment of the CCRP portfolio, including additional projects that were at an early stage of development (TRL 2).

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.

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.

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. A diagram of the portfolio of key technologies is shown in Figure ES-1.

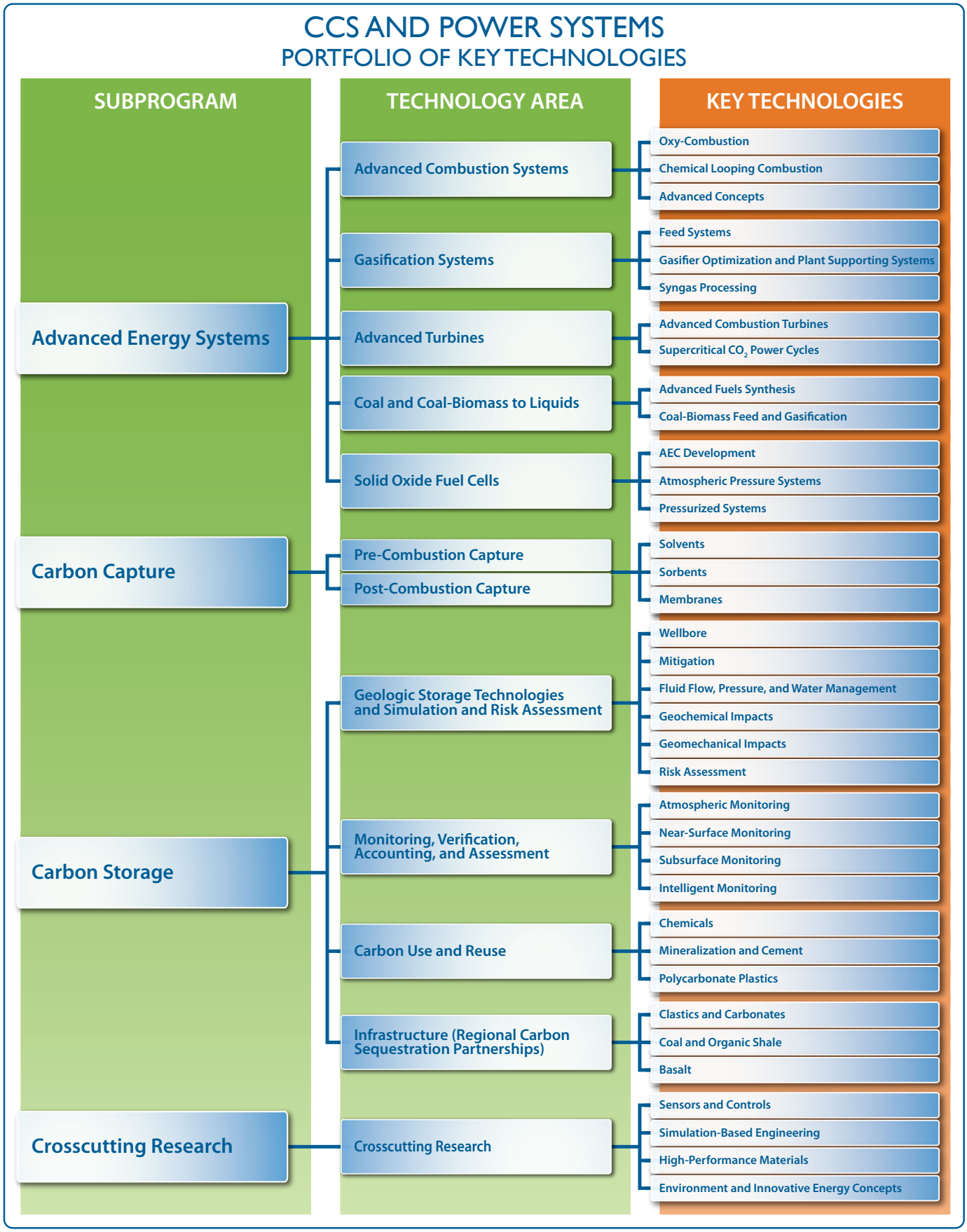

Figure ES-1. CCS and Power Systems Portfolio of Key Technologies

The FY14 assessment was focused on the 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 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 report.

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. One notable achievement since the issue of the FY12 TRA report is the successful start of operations of the Air Products and Chemicals, Inc., ICCS project. The capture, compression, and delivery of carbon dioxide (CO_2) from the first train of the PA-1 [Port Arthur 1] steam methane reformer (SMR) commenced on March 3, 2013. Full-scale operation of the project was initiated on March 7, 2013, with the startup of the second train of the SMR. As of December 2014, Air Products has captured and delivered over 1.5 million metric tons of CO_2 to the Denbury "Green" pipeline for use in enhanced oil recovery (EOR) operations (by others outside the CCRP).

In addition, the Archer Daniels Midland (ADM) ICCS project and the Southern Company Services (SCS)-Kemper Clean Coal Power Initiative (CCPI) project are under construction. Other significant accomplishments include the issuance of the first Class VI underground injection well permit by the Environmental Protection Agency (EPA) for the FutureGen 2.0 project, followed by a similar permit for the ADM project.

Technology availability for advancement is based on technology performance expectations, funding availability, demonstration program area priorities, and other factors. Although R&D projects typically focus on a single key technology, the demonstration projects frequently serve as a platform to advance multiple key technologies. It should be noted that some (19) R&D projects support the development of multiple technologies under different subtasks. Accordingly, these projects have been evaluated multiple times, resulting in multiple scores. Thus, for reporting purposes, these subtasks contribute individually to the determination of total project counts (see Table ES-2).

Figure ES-2 depicts the technology deployment pathway employed by the CCRP to accomplish its mission of developing technologies for potential commercial deployment. 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. For TRL definitions see Table ES-1.

Although this report focuses primarily on the TRA of the CCS and Power Systems program area, an overview of the TRA approach to technologies in the CCS Demonstrations program area is presented in the latter portion of this report (page 131).

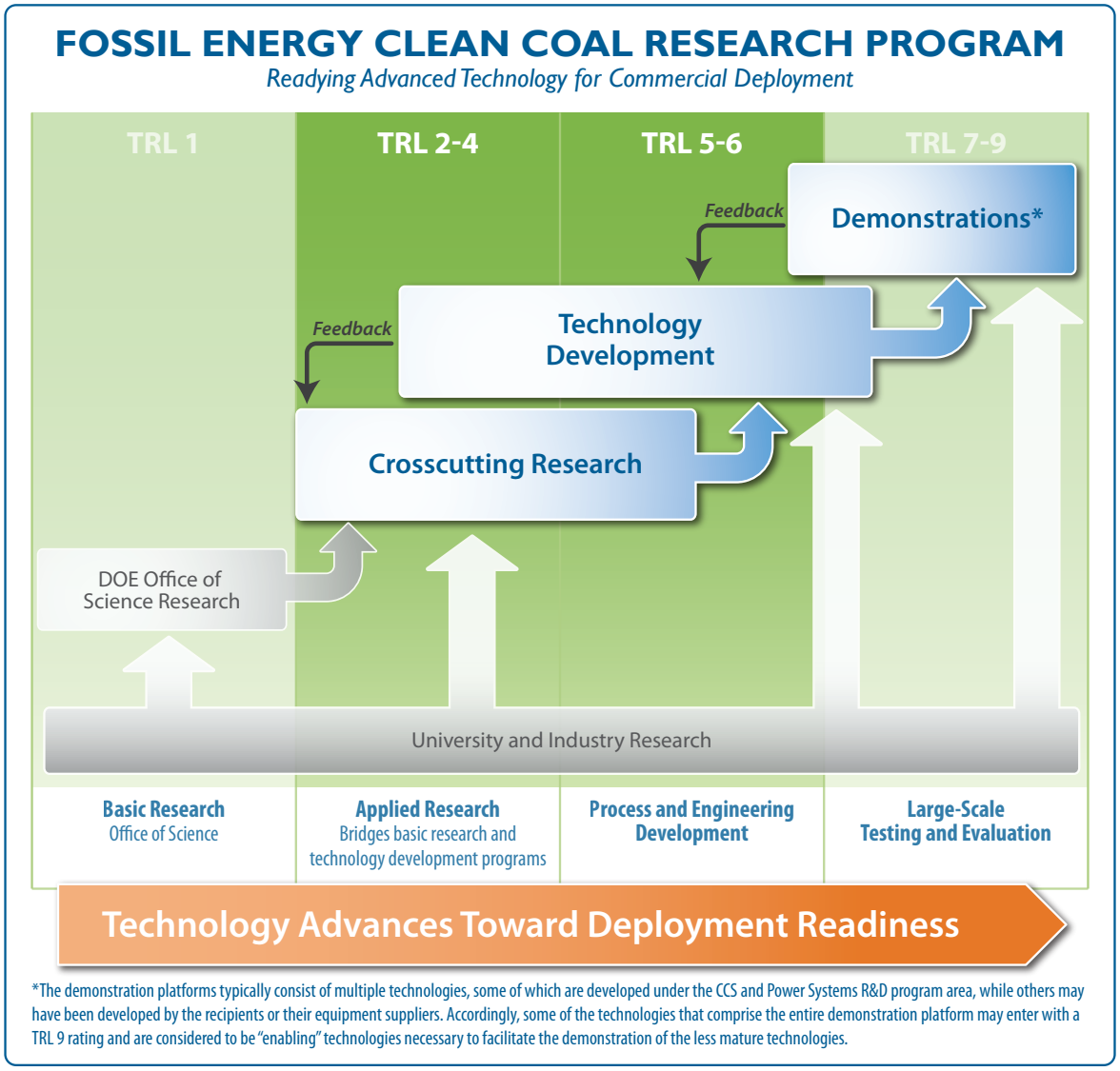

Figure ES-2. CCRP—Flow of Technology Advancement

TECHNOLOGY READINESS ASSESSMENT 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."[3] 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[4] provided the foundation for the assessment of CCRP R&D projects conducted by NETL.

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

4 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

TRL DEFINITIONS

Following the DOE TRA Guide, the Office of Fossil Energy developed a TRA Guide that provides TRL definitions and descriptions that were tailored to the R&D being conducted within the CCRP. Because advanced power-generation systems and carbon storage systems consist of distinctly different system functions, operating environments, and end-state deployment characteristics, separate TRL terminology and scales were developed to guide the assessment of these two individual systems. Refer to Table ES-1 for TRL terminology for advanced power-generation systems. A similar table was developed for carbon storage systems and is included as Table 2 in the body of this report. 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 ES-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).

TRA METHODOLOGY

To ensure sound, consistent, and reliable technology assessment results, an assessment team of subject matter experts and individuals knowledgeable in the execution of TRAs was selected to implement the process in a manner that considered the full portfolio of R&D projects that are active in the 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. 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; of the 423 active projects, 349 projects and tasks met the criteria for conducting a formal TRA. The evaluation teams gathered pertinent information, conducted an independent analysis, assessed their findings, reached team consensus, and documented the results of their evaluation, including a preliminary TRL score.

The preliminary TRL scores were then provided to those funding recipients primarily responsible for the conduct of the specific research (i.e., the individual Principal Investigators) to seek a consensus technology rating score. Once this step was completed, the scores were finalized and the results of this comprehensive evaluation are documented in this report.

An overview of the process used in this effort is depicted in Figure ES-3.

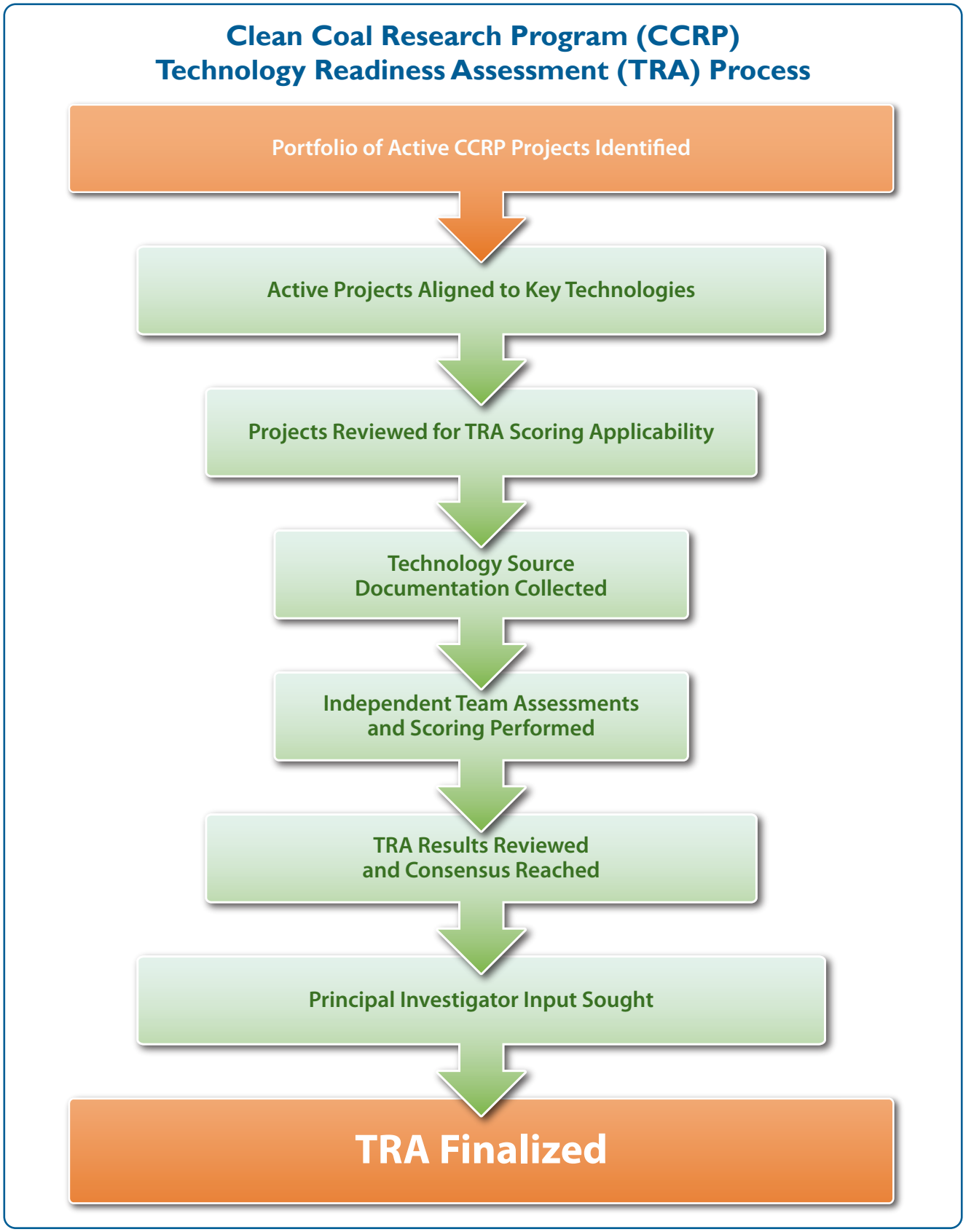

Figure ES-3. CCRP TRA Process Diagram

SUMMARY OF R&D RESULTS

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 ES-2. More detail regarding the individual key technologies can be found in Tables 5 through 16 in the main body of this report.

Table ES-2. **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**

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 ES-2, 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.

FULL-SCALE COMMERCIAL CCS 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 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, DOE's 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).

Via the CCS 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

FE's CCS and Power Systems R&D program area develops individual technologies to the point of full-scale commercial demonstration readiness. In general, this endpoint corresponds to technology rating levels from TRL 6 to TRL 7. The CCS 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 within a single demonstration platform.

The TRA discipline is an evolving 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. The PPA typically is completed and issued after DOE receives the final report from the recipient. Accordingly, the TRA was only completed for the CCS and Power Systems R&D portion of the CCRP. However, consistent with FE's efforts to provide informative detail on CCRP projects, more details related to the key technologies being advanced through the active demonstration platforms are provided in the CCS Demonstrations section of this report.

Building on its experience with the TRA process and recognizing the complexity of multiple technology integration 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 the Department of Defense (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 utilizes 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 of a specific technology configuration. If proven beneficial for evaluation and reporting of the status of the demonstration platforms, the SRL evaluations would be conducted along with the TRA evaluation as part of the PPA that DOE conducts after the completion of each demonstration. This aspect of technology assessment is now beginning to be evaluated by NETL.

CONCLUSION

In the CCS and Power Systems R&D program area, there are 53 technologies with TRL ratings ranging from 5 to 7. Of these, 14 technologies have been identified as strong candidates (TRL 6–7) for advancement into the CCS Demonstrations program area to continue their development for potential commercial use, and 50 technologies have attained a level of technology readiness (TRL 5–6) to be considered for advanced large-scale testing. The 11 projects that account for the overlap, received a TRL rating of 6 and require additional scrutiny to determine their progression strategy.

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 has assessed the lessons learned from the FY12 effort and made a number of improvements, which are reflected in this report. NETL has begun to translate those lessons into program management practices, technology status assessment and reporting—and the value of continuing these assessments 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 maturity status of the complex set of key technologies currently under development and the likelihood of successfully achieving the CCRP's objectives have 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 biannual basis.

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INTRODUCTION AND PURPOSE

FOSSIL ENERGY PROGRAM DRIVERS

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.[1] 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 (FE's) Clean Coal Research Program (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 the Department of Energy (DOE) representatives in response to these drivers. Ultimately, the CCRP is responsive to the DOE's 2014 Strategic Plan[2] and the fiscal year 2014 (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[3] 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."

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

2 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

3 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.

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.
- **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 research, development, and demonstration (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 the National Energy Technology Laboratory (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 research and development (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.

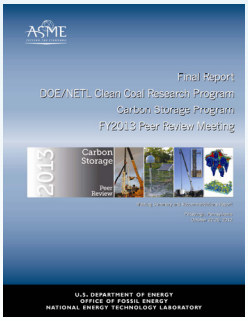
FE's CCRP is implemented by NETL's Strategic Center for Coal (SCC). The SCC conducts coal-related R&D under four subprograms:

- **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 CO_2 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.
- **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.

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



FE's advanced R&D program produces CCS technologies for application at both new and existing plants. The development of these innovative technologies leads to potential demonstration via four pathways: pre-combustion, advanced combustion, post-combustion, and capture from industrial sources. Pre-combustion refers to a process in which a hydrocarbon fuel is gasified to form a mixture of hydrogen (H_2) and carbon monoxide. Using shift reactors, the carbon monoxide is converted to CO_2, and the CO_2 is captured from the synthesis gas before it is combusted. Oxy-combustion (the principal form of advanced combustion currently being investigated) is a process in which a hydrocarbon fuel is combusted in pure or nearly pure oxygen rather than air, producing a mixture of CO_2 and water (H_2O) that can facilitate capture because pure CO_2 can easily be separated from the water. Post-combustion refers to capturing CO_2 from the stack gas after a fuel has been combusted in air. DOE's capture-related research is exploring a wide range of alternatives, including membranes, solid sorbents, and solvents. These efforts encompass not only improvements to state-of-the-art technologies but also development of advanced lower cost/higher efficiency concepts. The final pathway 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.

The baseline CCRP, supplemented by funding from the Recovery Act, will produce the data and knowledge needed to establish the technology base, reduce implementation risks by industry, and enable broader commercial deployment of CCS. The funding of revolutionary research for CCS will help the United States realize continued improvement in power-generation technology and potentially transform U.S. energy infrastructure.

PURPOSE

In FY12, NETL developed standard benchmarks and performed the first assessments of key technologies within its research portfolio (FY12 TRA report). This FY14 TRA 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 provides additional details concerning these efforts and depicts examples of recent products.

TECHNOLOGY READINESS LEVEL METHODOLOGY

The TRL methodology 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 yield an assessment of the technology development spanning progress from early research on basic principles through service conditions and size needed for the technology to perform when it is deployed or put into use. Technology development typically advances over a multiyear period and incrementally refines design until a suitably sized demonstration is successfully completed. TRLs are particularly useful in establishing a consistent set of terminology and a supporting evaluation process that can be used to benchmark a technology's current state of progress 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, the TRL methodology emerges as a useful tool in the planning of future R&D activities.

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[5] 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.

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[6]) 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.

4 Mankins, J., *Technology Readiness Level White Paper*. 1995, rev. 2004. Accessed October 2013. 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 October 2013. https://www.directives.doe.gov/directives/0413.3-EGuide-04a/view

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

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).

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.

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.

The CCRP conducts research that spans the full range of development and does so in large part in collaboration with university and industrial sector participation. 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.

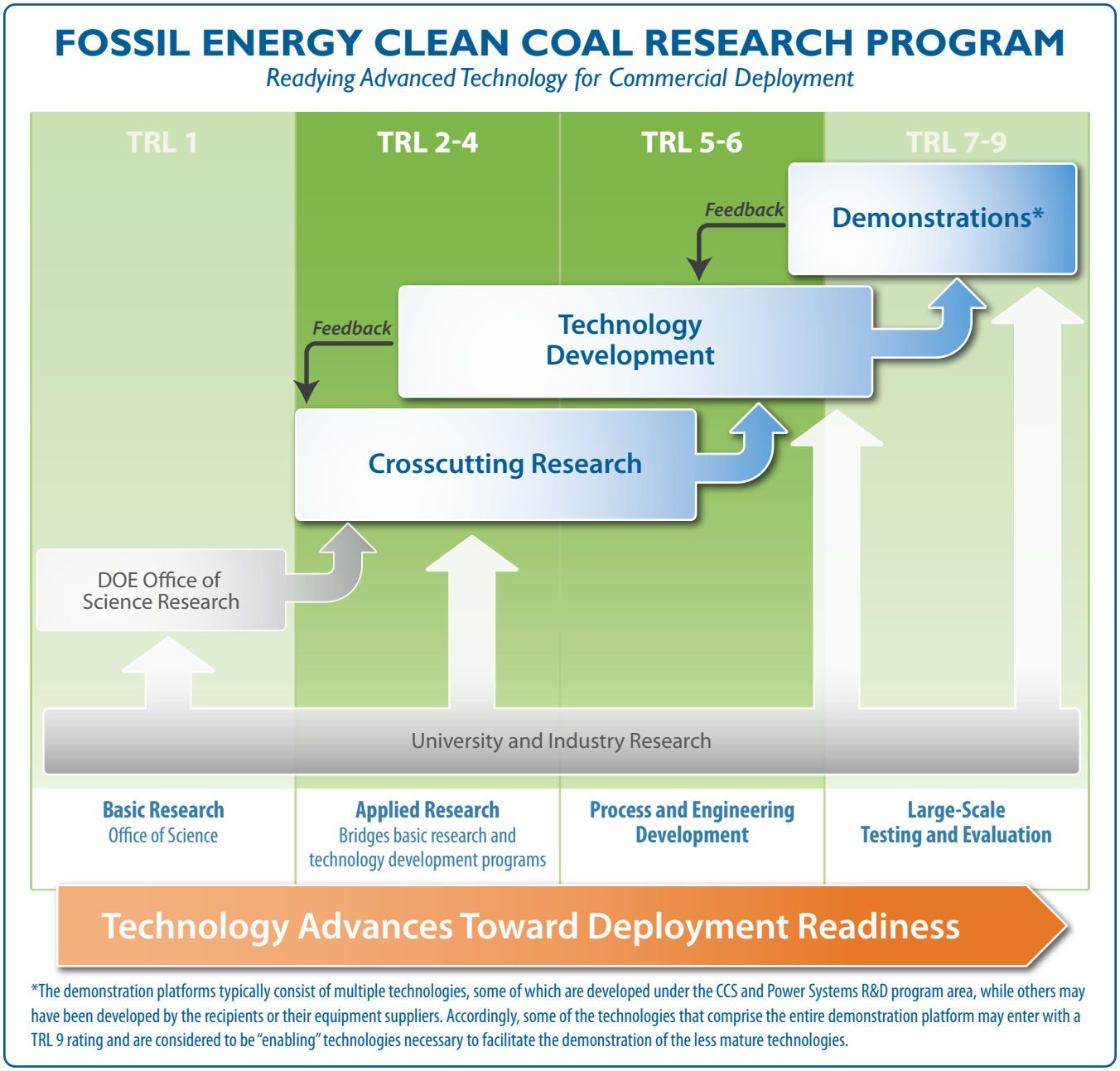


Figure 1. Schematic of DOE-FE Technology Readiness Levels

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 2.

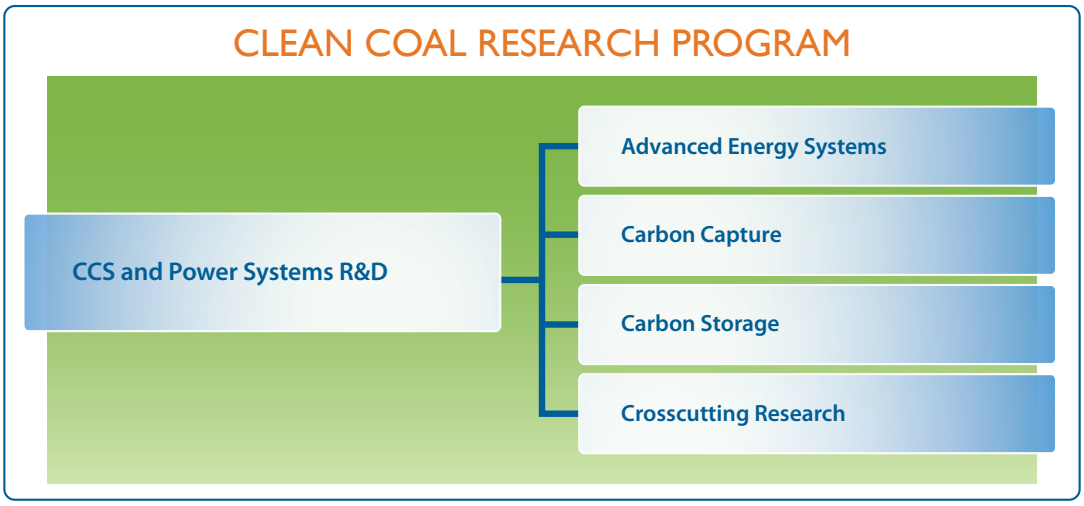


Figure 2. Fossil Energy Clean Coal Research Program FY14 Budget Structure

As of October 1, 2013, there were approximately 423 active projects within the CCRP R&D portfolio. The entire portfolio of projects was reviewed and considered for assessment as part of the evaluation process. Additionally, due to the improvements in scoring granularity on the FWPs, some projects were divided into tasks; all tasks not excluded due to the following criteria were scored. All projects awarded by or active on October 1, 2013, were scored with the following exclusions:

- Systems Analysis projects
- Small Business Innovation Research (SBIR)
- Industrial Carbon Capture and Storage (ICCS) Area 2
- Geologic Sequestration Site Characterization (GSSC)
- Geologic Sequestration Training and Research (GSTR)
- Projects awarded outside a competitive solicitation that do not have direct alignment to the current Technology Areas
- Support field work proposals (FWPs)

Consequently, 349 projects or tasks were scored for the FY14 TRA. This suite of projects and tasks that met the scoring criteria has 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 this formal TRA are presented in this report.

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 3.

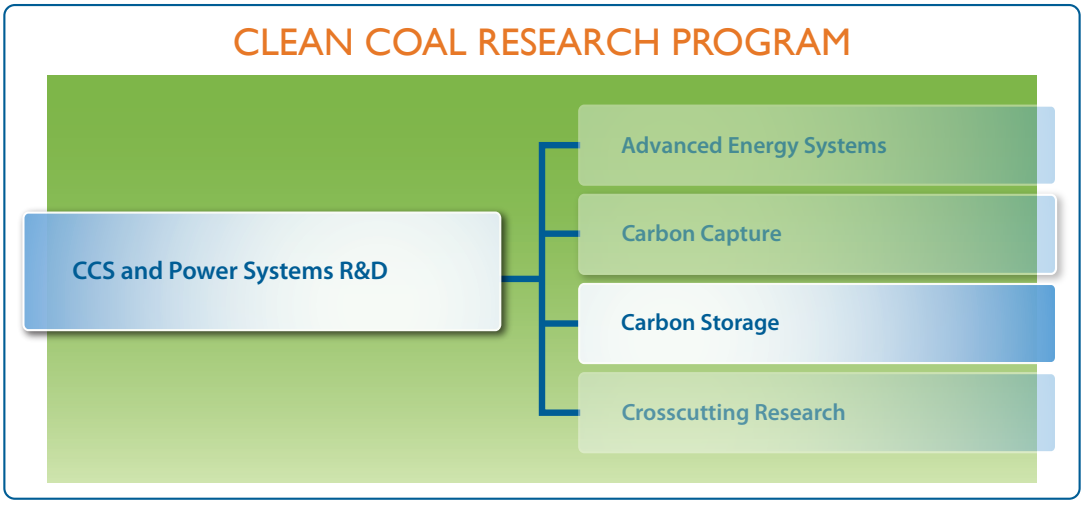


Figure 3. Carbon Storage Component of the Fossil Energy Clean Coal Research Program

The CCRPs four subprograms are divided into Technology Areas and then further subdivided into key technologies. Figure 4 provides an example, identifying Monitoring, Verification, Accounting, and Assessment as one of four Carbon Storage Technology Areas. "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?

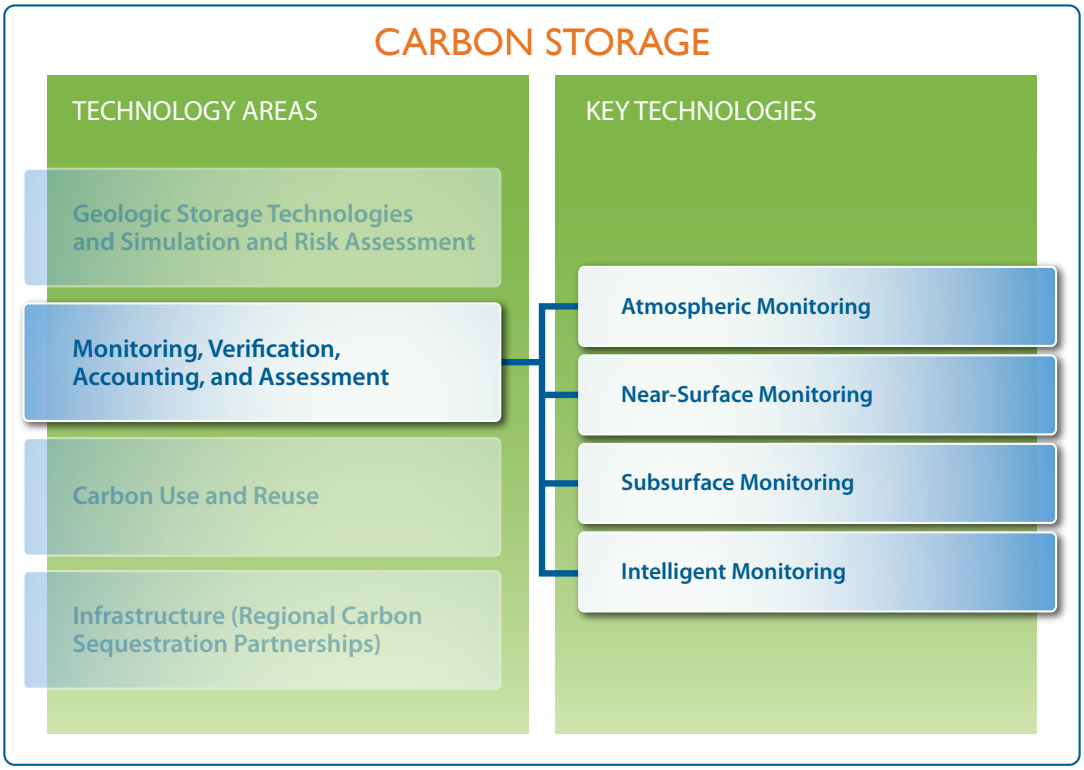


Figure 4. Example of Technology Area and Key Technologies Subdivision

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 5 and described in a subsequent narrative.

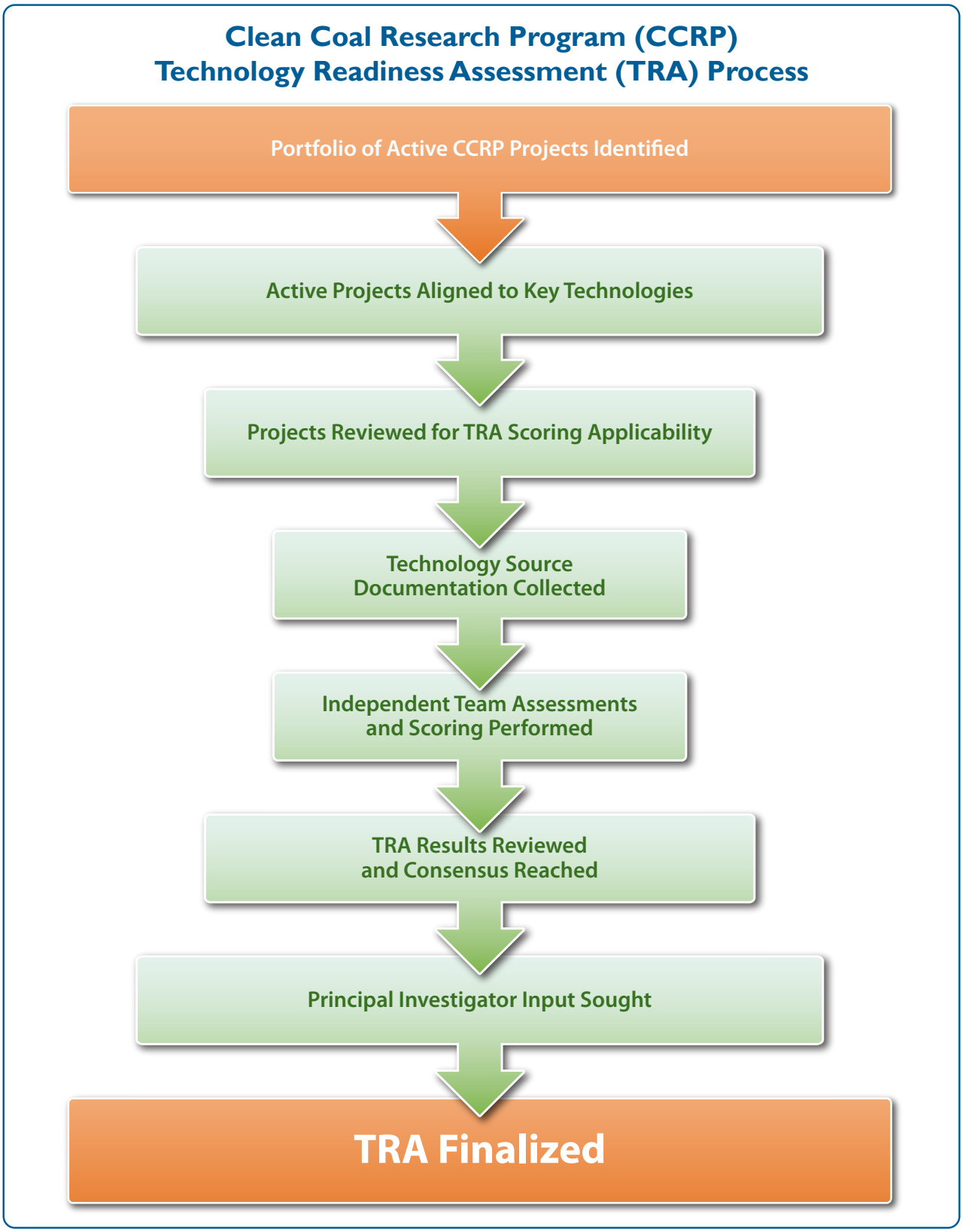


Figure 5. Process Flow for Conducting TRA

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,[8] 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 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.

8 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.

SUMMARY AND CONCLUSIONS

SUMMARY OF RESULTS

R&D 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 3.

Table 3. **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**

Table 3. **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	
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 4.

Table 4. **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 4. **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 4. **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 3, 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.

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

ADVANCED ENERGY SYSTEMS

The Advanced Energy Systems subprogram is developing a new generation of clean coal-fueled energy conversion systems capable of producing competitively priced electric power while reducing CO_2 emissions, with a focus on improving efficiency, increasing plant availability, reducing cooling water requirements, and achieving ultralow emissions of regulated pollutants. A key aspect of this area of research is targeted at improving overall system thermal efficiency, reducing capital and operating costs, and enabling affordable capture. The Advanced Energy Systems subprogram comprises five Technology Areas.

ADVANCED COMBUSTION SYSTEMS focus on new high-temperature materials and the continued development of high-efficiency oxy-combustion technologies amenable to capturing carbon at lower cost.

GASIFICATION SYSTEMS investigate the conversion of coal into clean syngas that can in turn be converted into electricity, chemicals, hydrogen, and liquid fuels to suit market needs.

ADVANCED TURBINES develops advanced technology for the integral electricity-generating component in a gasification-based clean energy plant fueled by hydrogen.

COAL AND COAL-BIOMASS TO LIQUIDS is focused on technologies to foster the commercial adoption of coal and coal-biomass gasification and the production of affordable liquid fuels and hydrogen in an environmentally acceptable manner.

SOLID OXIDE FUEL CELLS focuses on developing fuel-cell-powered novel atmospheric and pressurized systems that produce electric power from coal using integrated coal gasification.

ADVANCED ENERGY SYSTEMS

ADVANCED COMBUSTION SYSTEMS

Advanced combustion power generation from fossil fuels involves combustion in oxygen rather than air, or oxygen (O_2)-fired combustion. This type of system eliminates the introduction of nitrogen (N_2) (from air) into the combustion process, generating flue gas composed of water, CO_2, trace contaminants from the fuel, and any other gas constituents that infiltrated the combustion system. The high concentration of CO_2 (≈60 percent) and absence of N_2 in the flue gas simplify separation of the CO_2 for storage or beneficial use. Thus, O_2-fired combustion is an alternative approach to post-combustion capture for CCS for coal-fired systems. The Advanced Combustion Systems Technology Area research effort is focused on continued development of oxygen-fired combustion technologies.

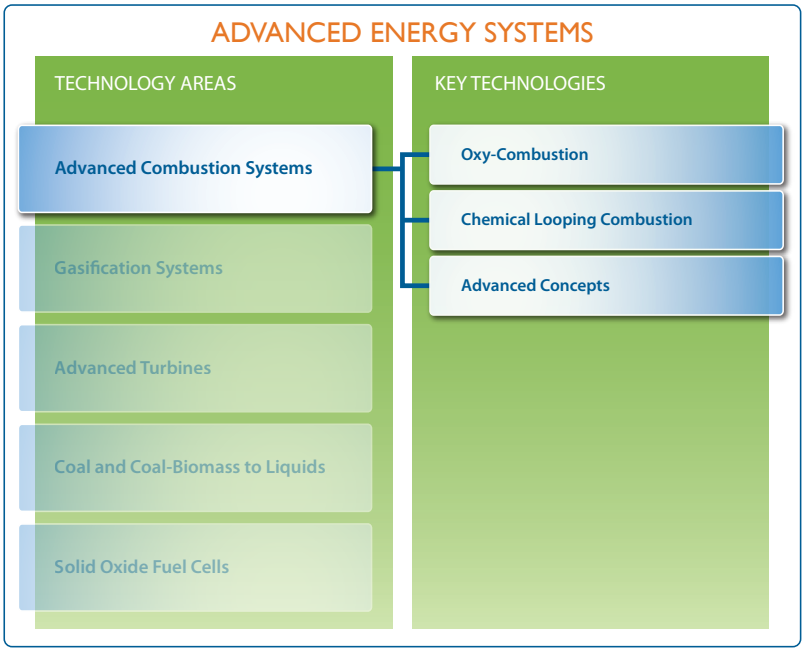


Figure 6. Advanced Combustion Systems Key Technologies

Targets

The Advanced Combustion Systems Technology Area supports the achievement of GPRA Endpoint Performance Target 2—*Advanced Energy Systems with CO_2 capture at no more than $40 per tonne of CO_2 captured by 2020.*

Benefits

Advanced combustion power plants produce flue gas that is rich in CO_2, simplifying the separation of CO_2 as compared to more dilute air-fired combustion systems. Emissions of N_2 compounds are nearly eliminated through the exclusion of air from the boiler, negating the need for nitrogen oxides (NO_x) control technologies. Pressurized systems offer an additional driving force for removal of mercury and acid gases by shifting the temperature at which these constituents condense, allowing for their removal in the liquid phase. In pressurized systems, water vapor condensation occurs at a much higher temperature than in atmospheric-pressure systems. As a result, the thermodynamic quality of the condensing heat is high and can be used for high-value purposes such as feed-water heating to improve power plant cycle efficiency. The capability to produce low-cost, coal-based electricity while eliminating nearly all air pollutants and potential GHG emissions makes advanced combustion one of the most promising technologies for energy plants of the future.

Critical Challenges

- Reduce the capital cost and energy consumption for a cryogenic air separation unit (ASU).
- Design oxygen-fired combustion boilers to take advantage of higher flame temperatures and lower gas volumes associated with nitrogen exclusion.
- Employ CO_2 purification and compression processes that minimize energy consumption.
- Utilize emissions control technologies that leverage the unique characteristics of the flue gas generated in oxygen-fired combustion systems to improve capital cost and reduce energy consumption.
- Reduce or eliminate excess O_2 in the concentrated CO_2 flue gas stream.
- Resolve the challenges of solids handling and reactor designs.

Projects Assessed

The TRLs of 6 projects were assessed in the Advanced Combustion Systems Technology Area: 4 in Oxy-Combustion and 2 in Chemical Looping Combustion. This collective body of work is being pursued to expand the state of knowledge and strengthen the technical basis for the ongoing and planned research in this area.

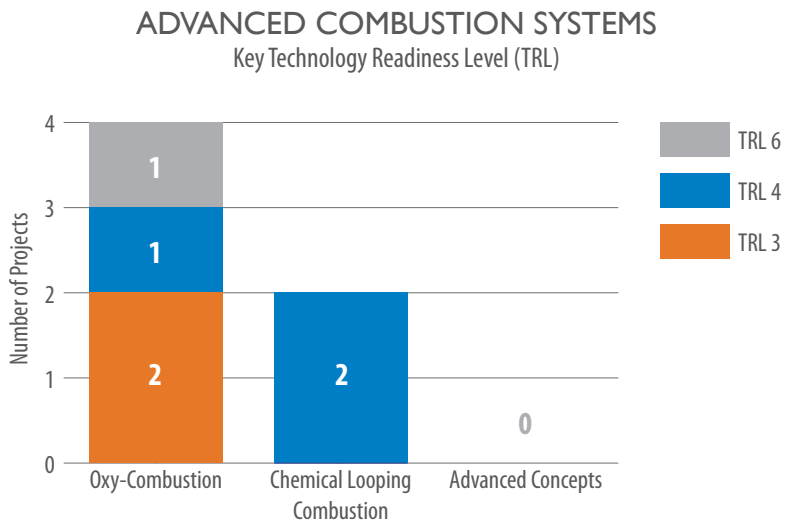


Figure 7. TRL Scores for Advanced Combustion Systems Projects

Rating Summary

The critical technology challenges related to Advanced Combustion Systems require a portfolio of technologies encompassing the three key technologies. For the FY14 assessment, the Advanced Concepts key technology did not include any active projects as defined in the TRL Methodology section. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the Advanced Combustion Systems technology emerges as a range of TRL values. The overall readiness of the Advanced Combustion Systems Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 3 to 6.

Technology Readiness Level Range for Advanced Combustion Systems

3–6

ADVANCED COMBUSTION SYSTEMS

KEY TECHNOLOGIES

OXY-COMBUSTION

4 PROJECTS
3–6 TRL RANGE

In an oxy-combustion process, an enriched O_2 stream is used instead of air for combustion. In this process, most of the N_2 is removed, yielding a stream that is at least 95 percent O_2. Combusting fossil fuel in a stream of nearly pure oxygen, or a mix of oxygen and CO_2, provides advantages for CO_2 capture and other emissions control in power plant applications. The oxy-combustion flue gas is primarily CO_2 and H_2O, simplifying CO_2 purification and compression for storage or beneficial use. Furthermore, the volume of flue gas could be as much as 75 percent less than that from air-fired combustion, allowing easier removal of pollutants (sulfur oxides, NO_x, mercury, particulates) from the flue gas. Because N_2 is removed from the air, NO_x production is also greatly reduced.

Oxy-combustion power production provides oxygen to the combustion process by separating oxygen from air. However, the capital cost, energy consumption, and operational challenges of oxygen separation are the most significant barrier to the use of oxy-combustion technology. Oxy-combustion system performance can be improved by two means: (1) lowering the cost of oxygen supplied to the system and (2) increasing the overall system efficiency. The R&D within the Advanced Combustion Systems program is aimed at strategies to improve oxy-combustion system efficiency and reduce capital cost, offsetting the challenges of oxygen production.

Four projects within the Advanced Energy Systems Advanced Combustion Systems portfolio that focus on improving oxy-combustion technologies were assessed. The current TRLs of this key technology range from 3–6 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

CHEMICAL LOOPING COMBUSTION

2 PROJECTS
4 TRL RANGE

In chemical looping systems, oxygen is introduced to the system via oxidation-reduction cycling of an oxygen carrier. The oxygen carrier is usually a solid, metal-based compound. It may be in the form of a single metal oxide, such as an oxide of copper (Cu), nickel (Ni), or iron (Fe); or a metal oxide supported on a high-surface-area substrate (e.g., alumina or silica) that does not take part in the reactions. For a typical chemical looping combustion (CLC) process, combustion is split into separate oxidation and reduction reactions that take place in multiple reactors. The metal oxide supplies oxygen for combustion in the fuel reactor, operated at elevated temperature, and is reduced by the fuel. The reaction in the fuel reactor can be exothermic or endothermic, depending on the fuel and the oxygen carrier. The combustion product from the fuel reactor is a highly concentrated CO_2 and H_2O stream that can be purified, compressed, and sent to storage or for beneficial use. The reduced metal carrier is then sent to the air reactor, which also operates at elevated temperatures, where it is regenerated to its oxidized state. The air reactor produces hot flue gas, which is used to create steam that drives a turbine, generating power. Current CLC R&D efforts are focused on development and refinement of high-capacity oxygen carriers that can withstand the harsh environment associated with CLC operation; development of effective and sustainable solids circulation and separation techniques; reactor design to support fuel and oxygen carrier choices; effective heat recovery and integration; and overall system design and optimization.

Two projects within the Advanced Energy Systems Advanced Combustion Systems portfolio focused on improving CLC technologies were assessed. The current TRL of this key technology is 4 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

ADVANCED CONCEPTS

0 PROJECTS
N/A TRL RANGE

The Advanced Combustion Systems program is targeting advanced concept areas that provide the potential for oxy-fuel combustion systems to exceed cost and performance goals, providing a pathway toward commercial deployment. Two currently targeted concepts are integration of oxy-fuel combustion with a supercritical CO_2 power cycle and magnetohydrodynamics (MHD) power generation.

The supercritical CO_2 power cycle operates in a manner similar to other turbine cycles, but uses CO_2 as the working fluid in the turbomachinery. It offers the potential for significant improvements in the efficiency and capital costs associated with oxy-fuel power generation. R&D is needed to design heat transfer surfaces and heat extraction locations in oxy-fuel combustion units optimized to the supercritical CO_2 power cycle. In an MHD system, power is generated by moving conductive, high-temperature gases through a magnetic field. The high temperatures generated in an oxy-fuel combustion environment could drive an MHD power system. An MHD system could be operated as a stand-alone power-generation system or conceivably integrated with a steam or supercritical CO_2 bottoming cycle. R&D needs in this area include process design and integration concepts supported by modeling and experimental analyses.

No projects under the Advanced Concepts key technology met the TRL assessment requirement (as explained on page 10); therefore zero projects were assessed in this key technology for the FY14 report.

ADVANCED COMBUSTION SYSTEMS

PORTFOLIO

Table 5. **Advanced Combustion Systems Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Oxy-Combustion			
Aerojet Rocketdyne **FE0009448**	Advanced Oxy-Combustion Technology Development and Scaleup for New and Existing Coal-Fired Power Plants	3	This project focuses on development of an oxygen-fired pressurized fluidized-bed combustor (oxy-PFBC). The oxy-PFBC operates at high pressure and improved efficiency, lowering capital and operating costs, and incorporates limestone injection to facilitate SO_2 removal, reducing emission control equipment costs. Specifically, this project will design, build, and test a small pilot-scale oxy-PFBC combustor to provide data necessary for scaleup.
Alstom Power, Inc. **NT0005290**	Recovery Act: Oxy-Combustion Technology Development for Industrial-Scale Boiler Applications	6	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.
Praxair, Inc. **FC26-07NT43088**	Recovery Act: Oxy-Combustion: Oxygen Transport Membrane Development	4	The focus of this project is the development of the oxygen transport membrane (OTM) technology for processing gaseous fuels. The OTM reduces oxygen production needs, lowering capital and operating costs, and produces a highly concentrated stream of CO_2, providing a low-cost, near-zero-emissions alternative for industrial processes used to process gaseous fuels. Specifically, this project will demonstrate a development-scale (≈160,000 scfd syngas/200 kWth equivalent) OTM oxy-combustion and reformer unit to support design of a pilot-scale OTM process.
Washington University in St. Louis **FE0009702**	Staged, High-Pressure Oxy-Combustion Technology: Development and Scaleup	3	This project is developing a staged, pressurized, oxy-combustor system. Fuel-staged combustion uses excess oxygen as a diluent to manage peak combustion temperatures, and combined with high-pressure operation, has the potential to reduce capital and operating costs relative to those of conventional systems. Specifically, this project will develop and test a laboratory-scale pressurized oxy-combustor to support design, development, and testing of a small pilot-scale prototype.
Key Technology—Chemical Looping Combustion			
Alstom Power, Inc. **FE0009484**	Alstom's Chemical Looping Combustion Technology with CO_2 Capture for New and Retrofit Coal-Fired Power	4	This project focuses on development of the limestone CLC system. The low-cost limestone oxygen carrier along with less-expensive more-efficient reactors drives down capital and operating costs relative to those of conventional systems. Specifically, this project involves addressing technology gaps and generating data to support scaleup via continuous, stable operation of a 1-MWe prototype system.
Babcock & Wilcox Power Generation Group, Inc. **FE0009761**	Commercialization of the Iron-Based Coal Direct Chemical Looping Process for Power Production with In Situ Carbon Dioxide Capture	4	This project focuses on development of an iron-based coal-direct chemical looping (CDCL) process. The CDCL reactor design leverages high oxygen carrier conversion rates and improved solids separation, reducing equipment size and complexity and driving down capital and operating costs relative to those of conventional systems. Specifically, this project involves bench-scale testing and modeling to address solids handling, carrier capacity, and techno-economic analysis to provide a basis for small pilot-scale testing.

ADVANCED ENERGY SYSTEMS

GASIFICATION SYSTEMS

Gasification is used to convert a solid feedstock, such as coal, petcoke, or biomass, into a gaseous form, referred to as synthesis gas or syngas, which is primarily hydrogen and carbon monoxide. Gasification can generate clean power with minimal CO_2 emissions by adding steam to the syngas in a water-gas-shift reactor to convert the carbon monoxide to CO_2 and to produce additional hydrogen. The hydrogen and CO_2 are separated—the hydrogen is used to make power and the CO_2 is sent to storage, converted to useful products or used for EOR. In addition to efficiently producing electric power, a wide range of transportation fuels and chemicals can be produced from the cleaned syngas; polygeneration of power, fuels, and chemicals is therefore a unique possibility afforded by gasification systems. The Gasification Systems program is developing technologies in three key technologies to reduce the cost and increase the efficiency of producing syngas: (1) Feed Systems, (2) Gasifier Optimization and Plant Supporting Systems, and (3) Syngas Processing.

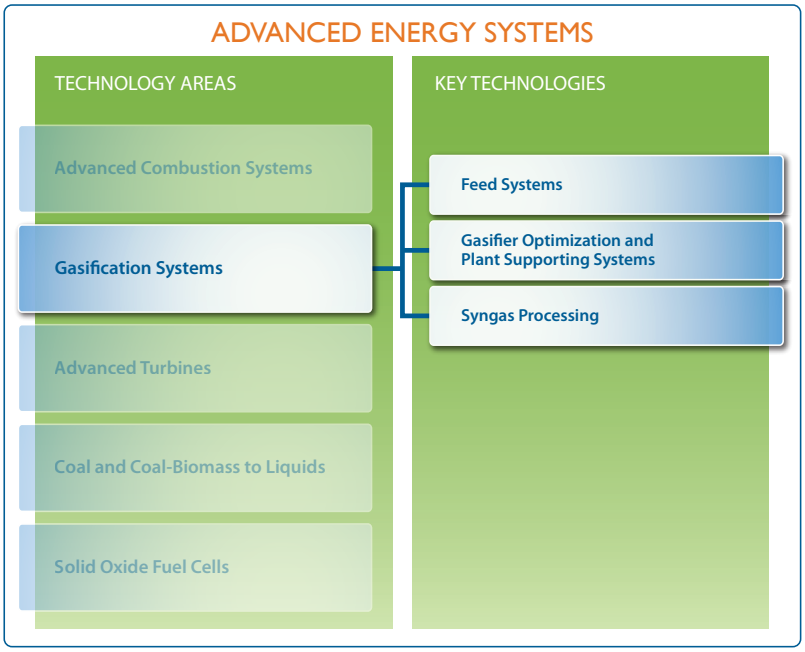


Figure 8. Gasification Systems Key Technologies

Targets

The Gasification Systems Technology Area supports the achievement of GPRA Endpoint Performance Target 2—*Advanced Energy Systems with CO_2 capture at no more than $40 per tonne of CO_2 captured by 2020.*

Benefits

Gasification technologies, in addition to efficiently producing electric power, provide a wide range of transportation fuels and chemicals that can be coproduced from the cleaned syngas, thereby providing the flexibility needed to capitalize on and support changing U.S. economic needs. Cleaning pollutant species from syngas and capturing CO_2 is easier and cheaper compared to conventional exhaust gas cleanup. As a result, advanced gasification provides a flexible technology option for using domestically available resources while meeting future environmental emissions standards. The Gasification Systems Technology Area research effort is developing a portfolio of technologies that will increase gasification efficiency, reduce capital and operations costs, and increase availability while reducing the environmental impact of coal utilization.

Critical Challenges

- Conventional cryogenic air separation for oxygen production is a mature technology with little opportunity for improvement. To reduce capital and operating costs, new technologies, such as those based on ion transport membranes (ITMs), are needed.
- Efficiency-boosting gas separation processes must be integrated into the plant, optimized with the temperature and pressure requirements of other systems, and meet product delivery specifications. For H_2 separation, technologies capable of producing CO_2 at high pressure to avoid significant recompression costs would enhance economics.
- Significant improvements in key components such as coal feed systems are essential to efficiently utilize domestic coal resources, including western low-rank coal.
- Low operational availability of gasifiers and gasification-based technologies is one of the barriers to commercial deployment of IGCC and syngas-based production of fuels and chemicals.

Projects Assessed

The TRLs of 21 projects were assessed in the Gasification Systems Technology Area: 4 in Feed Systems, 6 in Gasifier Optimization and Plant Supporting Systems, and 11 in Syngas Processing. This collective body of work is being pursued to expand the state of knowledge and strengthen the technical basis for the ongoing and planned research in this area.

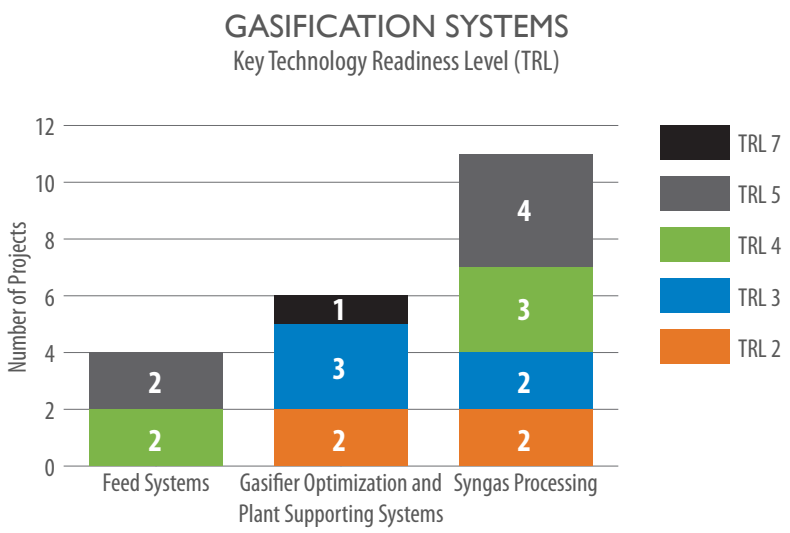


Figure 9. TRL Scores for Gasification Systems Projects

Rating Summary

The critical technology challenges related to Gasification Systems require a portfolio of technologies encompassing the three key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the Gasification Systems technology emerges as a range of TRL values. The overall readiness of the Gasification Systems Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 2 to 7.

Technology Readiness Level Range for Gasification Systems

2–7

GASIFICATION SYSTEMS

KEY TECHNOLOGIES

FEED SYSTEMS

Feed systems research is underway to reduce the cost and increase the efficiency, through design and advanced plant integration, of fuel and oxygen feed to commercial gasifiers. High-pressure solid feed systems will expand the use of our nation's western low-cost, low-rank coals for high-pressure gasifiers (currently limited to more expensive fuel), enable co-feeding of coal with other advantageous fuels (such as biomass), and encourage higher pressure (and therefore more efficient) operation of dry feed gasifiers. ITM technology will lower the cost of oxygen production through reduced capital costs, and result in more efficient integrated gasification combined cycle (IGCC) power plants through turbine integration, as compared to today's commercially available, energy-intensive technology for oxygen production—cryogenic air separation.

4
PROJECTS
4–5
TRL RANGE

Four projects within the Advanced Energy Systems Gasification Systems portfolio aimed at improving feed systems were assessed. The current TRLs of this key technology range from 4–5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

GASIFICATION OPTIMIZATION AND PLANT SUPPORTING SYSTEMS

Gasifier Optimization and Plant Supporting System technologies under development are targeted at increasing gasifier availability and efficiency, improving performance, and reducing the capital and operating costs of advanced gasification plants. Ongoing R&D projects are developing more durable refractory materials, creating models to better understand the kinetics and particulate behavior of fuel inside a gasifier, and developing practical solutions to mitigate the plugging and fouling of syngas coolers.

6 PROJECTS
2–7 TRL RANGE

Six projects within the Advanced Energy Systems Gasification Systems portfolio focused on gasification optimization technologies and plant supporting systems were assessed. The current TRLs of this key technology range from 2–7 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

SYNGAS PROCESSING

Syngas processing research and development underway emphasizes technologies that can be efficiently integrated into the plant, optimized with the temperature and pressure requirements of other systems, and meet product delivery specifications. A major cost element in gasification plants is converting raw syngas into a pure and specific gas used to create the plant's target product suite. High-hydrogen, low-methane (CH_4), ultraclean syngas is versatile and can be used for power production with CO_2 capture, fuels or chemicals production, and for many polygeneration applications. 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—often significantly lower than the EPA required levels for power plants.

11 PROJECTS
2–5 TRL RANGE

Eleven projects within the Advanced Energy Systems Gasification Systems portfolio focused on syngas processing R&D were assessed. The current TRLs of this key technology range from 2–5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

GASIFICATION SYSTEMS
PORTFOLIO

Table 6. **Gasification Systems Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Feed Systems			
Aerojet Rocketdyne **FE0012062**	Dry Solids Pump Coal Feed Technology Program	5	This Aerojet Rocketdyne 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. 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. This would increase the efficiency of the gasifier and reduce plant capital, maintenance, and operating costs, resulting in less than half the lifecycle cost (capital and operating combined) of the state-of-the-art dry solids lockhopper feed system, and is also expected to perform with at least twice the mechanical efficiency of conventional feed systems.
Air Products and Chemicals, Inc. **FC26-98FT40343.1**	Recovery Act: Development of Ion Transport Membrane Oxygen Technology for Integration in IGCC and Other Advanced Power-Generation Systems [Ceramic Production]	4	This Air Products and Chemicals, Inc., project focuses on increasing the efficiency and reducing the capital cost of O_2 production through development and demonstration of ITM technology. ITM uses mixed-ion and electron-conducting materials to produce high-temperature/high-purity O_2 at significantly lower capital than state-of-the-art cryogenic O_2 production systems. Specifically, this project will demonstrate a pilot-scale ITM O_2 production system and construct a facility capable of producing the complex modules at a commercially relevant rate.

Table 6. **Gasification Systems Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Air Products and Chemicals, Inc. **FC26-98FT40343.2**	Recovery Act: Development of Ion Transport Membrane Oxygen Technology for Integration in IGCC and Other Advanced Power-Generation Systems [Ion Transport Membrane]	4	This Air Products and Chemicals, Inc., project focuses on increasing the efficiency and reducing the capital cost of O_2 production through development and demonstration of ITM technology. ITM uses mixed ion and electron conducting materials to produce high-temperature/high-purity O_2 at significantly lower capital than state-of-the-art cryogenic O_2 production systems. Specifically, this project will demonstrate a pilot-scale ITM O_2 production system, and construct a facility capable of producing the complex modules at a commercially relevant rate.
Air Products and Chemicals, Inc. **FE0012065**	Development of Ion Transport Membrane Oxygen Technology for Low-Cost and Low-Emission Gasification and Other Industrial Applications	5	This Air Products and Chemicals, Inc., project focuses on increasing the efficiency and reducing the capital cost of O_2 production through development and demonstration of ITM technology. ITM uses mixed ion and electron conducting materials to produce high-temperature/high-purity O_2 at significantly lower capital than state-of-the-art cryogenic O_2 production systems. Specifically, this project will demonstrate a pilot-scale ITM O_2 production system, and construct a facility capable of producing the complex modules at a commercially relevant rate.
Key Technology—Gasifier Optimization and Plant Supporting Systems			
General Electric Company **FE0007859**	Feasibility Studies to Improve Plant Availability and Reduce Total Installed Cost in IGCC Plants	2	This General Electric Company project focuses on studying the feasibility of improving plant availability and reducing total installed costs in IGCC plants, by developing and improving operating methodologies, simulations, and control philosophies. The project targets reducing the time to technological maturity and enabling plants to 90 percent availability in a shorter period of time and at a lower installed cost. Specifically, this project will develop techno-economic studies using cost and availability data.
Institute of Gas Technology **FE0008350**	Development of Prototype Commercial Gasifier Sensor	7	This Gas Technology Institute project focuses on improving flame sensors' design, reliability, and sensitivity. 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.
Institute of Gas Technology **FE0012122**	Hybrid Molten Bed Gasifier for High-Hydrogen Syngas Production	2	This Gas Technology Institute project is conducting techno-economic evaluations and laboratory testing of a hybrid molten bed (HMB) gasification process with coal and natural gas co-feeding to produce syngas with high hydrogen-to-carbon-dioxide ratio. HMB gasification has the potential for improvement in operational performance and reliability of advanced coal-based power and liquid fuels generation compared to conventional gasification processes. Lowered cost and increased performance of high-hydrogen syngas production would enable liquid fuels production or power generation with decreased cost and lower environmental emissions.
NETL-ORD **FWP-2012.03.03.2**	Advanced Gasification—Task 2: Refractory Improvement	3	This NETL Office of Research and Development (ORD) project involves development of a database of slag properties (chemistry, viscosity, etc.) to provide an understanding of refractory wear as well as potential wear mitigation methods by testing various ash and slag chemistries against commercial and newly developed refractory materials. The project includes work to design new refractory materials that can match or exceed current refractory performance at a lower cost and with less environmental impact. The target is an affordable refractory material that will provide superior service life regardless of the feedstock used, offering the gasifier operator true fuel flexibility and the opportunity to achieve the industry's goal of 90+ percent online availability.
Ohio State University Research Foundation **FE0012136**	Chemical Looping Gasification for Hydrogen Enhanced Syngas Production in the Reaction Mixture Carbon Dioxide Capture	3	This Ohio State University project will further demonstrate the technical and economic advantages of a chemical looping gasification (CLG) process in context of IGCC and coal-to-liquid plants. Project objectives are to (1) improve oxygen carrier performance, (2) demonstrate the CLG process at bench scale to achieve greater than 98 percent coal conversion, (3) identify the effects and fates of sulfur, nitrogen, and other trace contaminants, (4) model cold-flow at sub-pilot scale, and (5) perform a comparative techno-economic analysis that validates the feasibility and attractiveness of the CLG system. Commercialized CLG technology is expected to improve the efficiency of coal-based gasification systems for both electricity generation and liquid fuels production while minimizing their carbon footprints.

Table 6. **Gasification Systems Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Reaction Engineering International **FE0007952**	Mitigation of Syngas Cooler Plugging and Fouling	3	This Reaction Engineering International (REI) project is focused on developing a better understanding of syngas cooler plugging and fouling principles, in order to formulate concepts for mitigation of these problems to improve gasification plant availability and reliability. Improvements in availability and reliability of the syngas cooler would directly reduce the cost of electricity (COE) in IGCC plants and costs of other products from syngas. Specifically, REI is conducting experiments and computational fluid dynamics (CFD) modeling to develop designs for deposit removal, with the most promising concepts to be validated during field testing.
Key Technology—Syngas Processing			
Air Products and Chemicals, Inc. **FE0013363**	Advanced Acid Gas Separation Technology for Clean Power and Syngas Applications	5	Air Products has developed a proprietary alternative to conventional syngas cleanup, combining a sour pressure swing adsorption (PSA) step that separates CO_2 and hydrogen sulfide (H_2S) from the desired products, and a tailgas disposition block that separates the sulfur-containing compounds and purifies the CO_2 to a sequestration-grade product. Specifically, Air Products will test a two-bed PSA unit on a slipstream of authentic, high-hydrogen syngas based on low-rank coal at the National Carbon Capture Center (NCCC); also, a multibed process development unit (PDU) will be operated, refining the reliability of predictions of PSA performance at commercial scale. The information obtained from the two-bed PSA unit and the PDU will be combined to build a techno-economic assessment of PSA utilization for methanol production, as well as to update techno-economic assessments of the technology for IGCC.
Eltron Research, Inc. **FC26-05NT42469**	Recovery Act: Scaleup of Hydrogen Transport Membranes for IGCC and FutureGen Plants	4	Eltron Research and Development, Inc., is developing a hydrogen transport membrane (HTM) system for hydrogen separation and CO_2 capture from shifted synthesis gas by designing and testing a pre-commercial module HTM system, with results to be used to update process models and for techno-economic analysis. Specifically, the project targets improvements in membrane characteristics, including higher permeability, higher selectivity, and lower membrane cost. Increased efficiency and directly resulting cost reductions come by operating the transport membranes at higher temperature (in combination with warm-gas-cleanup technology being developed).
Institute of Gas Technology **FE0011958**	Low-Cost High-H_2 Syngas Production for Power and Liquid Fuels	2	Gas Technology Institute will establish the proof-of-concept of a metal-polymeric membrane technology in improving performance of gasification systems in production of power, hydrogen, and liquid fuels from coal co-fed with natural gas. Specifically, laboratory studies will be conducted to obtain critical design data for an integrated multicontaminant removal process, techno-economic analyses performed to integrate these technologies with a Pratt & Whitney Rocketdyne gasifier, and comparison made with current hydrogen-from-coal technologies. Benefits of the technology include significant reductions in the cost of producing power with 90 percent carbon capture, and of producing diesel fuel, from coal.
NETL-ORD **FWP-2012.03.03.5**	Advanced Gasification—Task 5: Warm Gas Cleanup	3	This NETL ORD project is developing palladium (Pd) sorbents at lab and pilot scale for capture of trace metals (mercury, arsenic, selenium, phosphorus, antimony, and cadmium) from IGCC plants to meet or exceed EPA's standard limits for contaminants, and to avoid poisoning of downstream process elements such as catalysts and fuel cell electrodes. ORD is also developing a novel warm-gas reactor to allow for capture in one step to reduce the process footprint, costs, and complexity; and increase the certainty of the final disposition of the trace elements. A benefit of removing contaminants at elevated temperatures (up to 550 °F) is preserving the higher thermal efficiency of the IGCC system.
Praxair, Inc. **FE0004908**	Advanced Hydrogen Transport Membranes for Coal Gasification	5	The Praxair HTM project targets improvements in H_2-CO_2 separation membrane characteristics, including higher permeability, higher selectivity, and lower membrane cost. Specifically, the project work will scale-up current HTM technology to 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. Module performance will be evaluated using coal-derived syngas from an operating gasifier. Increased efficiency and directly resulting cost reductions come by operating the transport membranes at higher temperature (in combination with warm-gas-cleanup technology being developed). HTM technology will be versatile, applicable to both IGCC with over 90 percent carbon capture, and having the ability to make chemical grade hydrogen for liquid fuel, chemicals synthesis, and polygeneration applications.

Table 6. **Gasification Systems Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Research Triangle Institute **FE0000489.1**	Recovery Act: High-Temperature Syngas Cleanup Technology Scaleup and Demonstration Project [High-Temperature Desulfurization Process (HTDP)]	5	Research Triangle Institute's (RTI) warm syngas cleanup technology removes the most significant coal contaminants from syngas at high temperature, improving thermal and environmental performance of syngas cleanup technology. Specifically, the project consists of designing, building, and testing the HTDP at pre-commercial scale 50 MWe equivalent to remove more than 99.9 percent of the sulfur from coal-derived syngas. Techno-economic studies have shown that RTI's warm syngas cleanup technology, when integrated with 90 percent CO_2 capture, has the potential to significantly reduce the capital and operating cost of an IGCC plant, resulting in lower COE.
Research Triangle Institute **FE0000489.3**	Recovery Act: High-Temperature Syngas Cleanup Technology Scaleup and Demonstration Project [Trace Contaminant Removal Process (TCRP)]	4	RTI's warm syngas cleanup technology removes the most significant coal contaminants from syngas at high temperature, improving thermal and environmental performance of syngas cleanup technology. Specifically, the project consists of designing, building, and testing the HTDP at pre-commercial scale 50 MWe equivalent to remove more than 99.9 percent of the sulfur from coal-derived syngas. Techno-economic studies have shown that RTI's warm syngas cleanup technology, when integrated with 90 percent CO_2 capture, has the potential to significantly reduce the capital and operating cost of an IGCC plant, resulting in lower COE.
Research Triangle Institute **FE0012066**	Benefits of Integrating Aerojet Rocketdyne and RTI Advanced Gasification Technologies for Hydrogen-Rich Syngas Production	2	RTI will assess the potential for integration of advanced technologies to substantially reduce capital and production costs for hydrogen-rich syngas with near-zero emissions from coal gasification for power production with carbon capture and for coal-to-liquids (specifically methanol) with carbon capture. Specifically, integrated technologies considered in the analysis will include those already tested successfully at pilot scale—Pratt & Whitney Rocketdyne gasifier (including advances in dry solids feed systems) and RTI warm gas cleanup—with a new and innovative water-gas-shift technology, to show how multiple advanced technologies will leverage each other for significant cost and efficiency gains.
Southern Research Institute **FE0012054**	High-Hydrogen, Low-Methane Syngas from Low-Rank Coals for Coal-to-Liquids Production	3	Southern Research Institute will design and analyze a modified, advanced gasification platform for the conversion of low-rank coals to syngas for coal-to-liquid and gasification combined cycle applications. Specifically, this will involve development, testing, and optimization of steam-reforming catalysts for converting tars, C_{2+} hydrocarbons, ammonia, and CH_4 in high-temperature and sulfur environments, typical of syngas from low-rank coal gasification. Improved catalysts would increase the H_2:carbon monoxide ratio of the syngas and reduce downstream fouling costs and efficiency losses, which would support the commercialization of a high-temperature, sulfur-tolerant steam reforming catalytic process to reduce the cost of coal-based gasification cleanup, reduce carbon emissions and increase the efficiency of low-rank coal gasification for production of electricity and coal-to-liquids.
TDA Research, Inc. **FE0012048**	Advanced Reactor Design for Integrated Water-Gas-Shift/Pre-Combustion CO_2 Capture	5	TDA Research, Inc., 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 (production of methanol, a precursor for gasoline production) that process low-rank coals and woody biomass. Specifically, the new system will use a warm gas CO_2 scrubber integrated with a water-gas-shift catalyst to capture greater than 90 percent of carbon emissions. With expected net plant efficiency 3–5 percent higher than plants using Selexol™ for CO_2 capture, the technology would significantly reduce the cost of carbon capture over the current state-of-the art, reduce carbon emissions, and have favorable impact on cost of production of electricity and value-added products from coal-based gasification systems.
Worcester Polytechnic Institute **FE0004895**	Engineering Design of Advanced H_2 CO_2 Pd and Pd/Alloy Composite Membrane Separations and Process Intensification	4	The Worcester Polytechnic Institute HTM project targets improvements in H_2-CO_2 separation membrane characteristics, including higher permeability, higher selectivity, and lower membrane cost. Specifically, the project will include R&D in improved membrane design, leading to the demonstration testing of the process at the pre-engineering/pilot scale of 2 pounds per day of H_2. Increased efficiency and directly resulting cost reductions come by operating the transport membranes at higher temperature (in combination with warm-gas-cleanup technology being developed). HTM technology will be versatile, applicable to both IGCC with over 90 percent carbon capture, and having the ability to make chemical-grade H_2 for liquid fuel, chemicals synthesis, and polygeneration applications.

ADVANCED ENERGY SYSTEMS

ADVANCED TURBINES

The efficiency of combustion turbines has steadily increased as advanced technologies have provided manufacturers with the ability to produce highly advanced turbines that operate at very high temperatures. Further increases in efficiency are possible through the continued development of advanced components, combustion technologies, material systems, thermal management, and novel turbine-based cycles. 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 and provide tangible benefits to the public in the form of lower cost COE, reduced emissions of criteria pollutants, and carbon capture options.

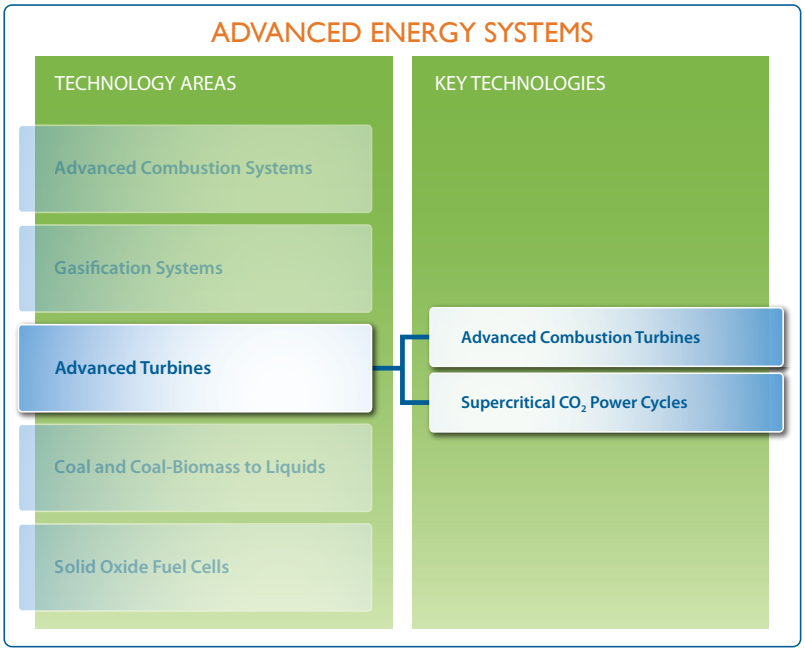


Figure 10. Advanced Turbines Key Technologies

Targets

The Advanced Turbines Technology Area supports the achievement of GPRA Endpoint Performance Target 2—*Advanced Energy Systems with CO_2 capture at no more than $40 per tonne of CO_2 captured by 2020.*

Benefits

System studies show that hydrogen turbines operating at 2,650 °F provide ≈$19/tonne reduction in CO_2 capture cost. Advanced combined cycle turbines operating at >3,100 °F have the potential to provide an additional $20/tonne reduction. Indirectly heated supercritical CO_2 power cycles offer benefits in the form of 7 percent efficiency improvement over state-of-the-art pulverized coal (PC) plants. Directly heated cycles provide a gateway to low-cost CO_2 capture for both coal and natural gas. Development of advanced turbine technologies ensures the effective use of U.S. energy supplies and helps maintain the United States position as a global leader in advanced turbine technologies.

Critical Challenges

- NO_x emissions need to remain in single digit ppm while firing temperature increases ≈450 °F using natural gas or coal-derived H_2.
- Advanced manufacturing techniques required for high performance turbomachinery.
- Thermal coating materials are not suitable for higher firing temperatures.
- Improved cooling designs needed to protect blades under increased thermal loads.
- Advanced components that will support whole machine optimization.
- Low availability of certified materials for use with supercritical CO_2.
- Design of high-temperature and -pressure oxy-fuel combustion systems adequate for direct-fired supercritical CO_2 systems.

Projects Assessed

The TRLs of 41 projects were assessed in the Advanced Turbines Technology Area: 39 in Advanced Combustion Turbines, and 2 in Supercritical CO_2 Power Cycles. This collective body of work is being pursued to expand the state of knowledge and strengthen the technical basis for the ongoing and planned research in this area.

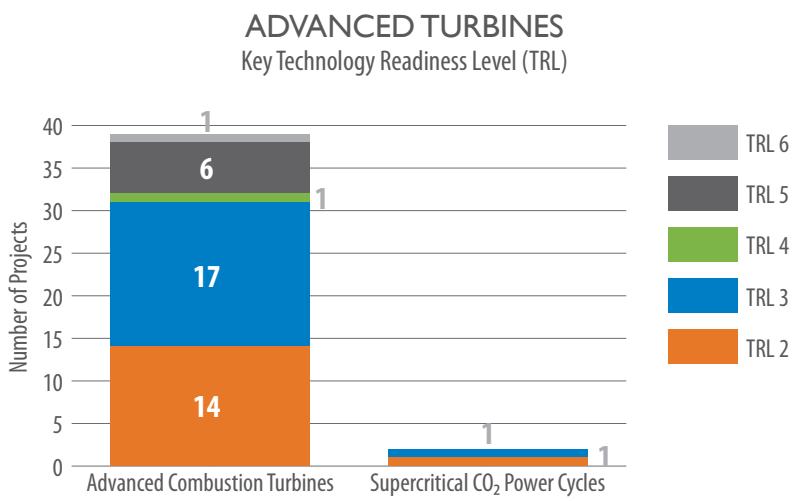


Figure 11. TRL Scores for Advanced Turbines Projects

Rating Summary

The critical technology challenges related to Advanced Turbines require a portfolio of technologies encompassing the two key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the Advanced Turbines technology emerges as a range of TRL values. The overall readiness of the Advanced Turbines Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 2 to 6.

Technology Readiness Level Range for Advanced Turbines

2–6

ADVANCED TURBINES

KEY TECHNOLOGIES

ADVANCED COMBUSTION TURBINES

39 PROJECTS
2–6 TRL RANGE

Advanced combustion turbines is focused on the development of components and combustion systems for advanced gas turbines that are capable of combined cycle efficiency greater than 65 percent (baseline natural gas, lower heating value, fuel-to-bus bar) and support load following capabilities to meet the demand of a modern grid. Reaching these targets will require broad R&D efforts that will allow higher turbine inlet temperatures (on the order of 3,100 °F), manage cooling requirements, minimize leakage, advance compressor and expander aerodynamics, advance the performance of high-temperature load-following low-NO_x combustion systems, and overall lead to improved efficiency of the gas turbine machine in a combined cycle application. The research will address component development for turbine systems fueled with natural gas and coal-derived fuels, including hydrogen and syngas, in combined cycle applications with pre-combustion carbon capture.

Thirty-nine projects within the Advanced Energy Systems Advanced Turbines portfolio focused on advanced combustion turbines development were assessed. The current TRLs of this key technology ranged from 2–6 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

SUPERCRITICAL CO_2 POWER CYCLES

The supercritical CO_2 power cycle operates in a manner similar to other turbine cycles, but it uses CO_2 as the working fluid in the turbomachinery. The cycle is operated above the critical point of CO_2 so that it does not change phases (from liquid to gas), but rather undergoes drastic density changes over small ranges of temperature and pressure. This allows a large amount of energy to be extracted at high temperatures from equipment that is relatively small in size. Supercritical CO_2 turbines can have a gas path diameter as small as a few inches compared to several feet for utility-scale combustion turbines or steam turbines. The R&D focus will be on components for indirectly heated fossil fuel power cycles with turbine inlet temperature at or above 1,400 °F (760 °C) and oxy-fuel combustion for directly heated supercritical CO_2-based power cycles.

2 PROJECTS
2–3 TRL RANGE

Two projects within the Advanced Energy Systems Advanced Turbines portfolio aimed at improving capabilities of supercritical CO_2 power cycles were assessed. The current TRLs of these projects are 2 and 3 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

ADVANCED TURBINES
PORTFOLIO

Table 7. **Advanced Turbines Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Advanced Combustion Turbines			
Ames Laboratory **FWP-AL05205018**	Analysis of Gas Turbine Thermal Performance	4	This project will develop CFD-based analysis tools for analyzing heat transfer issues in turbines. Turbine aerodynamics and heat transfer research will develop advanced cooling technology that will allow for higher firing temperatures, which translate into increased cycle efficiency. Specifically, this project will develop, evaluate, and apply CFD-based analysis tools that can properly account for the steady and unsteady three-dimensional (3-D) heat transfer from the hot gas in the turbine blade/vane passages through the turbine material system to the internal cooling passages as a function of the cooling strategy and the hot-gas and coolant compositions, mass flow rates, and temperatures.
Florida Turbine Technologies, Inc. **FE0006696**	Demonstration of Enabling Spar-Shell Cooling Technology in Gas Turbines	5	This project will demonstrate spar-shell airfoil technology to improve options for IGCC airfoil design. Turbine aerodynamics and heat transfer research will develop advanced cooling technology that will allow for higher firing temperatures, which translate into increased cycle efficiency. Specifically, this project will analyze, fabricate, assemble, install, and test prototype airfoils to validate performance in a commercial turbine application.
General Electric Company **FC26-05NT42643.1**	Recovery Act: Advanced Hydrogen Turbine Development—Combustion	6	This project will focus on advancing state-of-the-art industrial-frame turbine technology for hydrogen-fueled turbine machinery. Advanced turbine components will improve the efficiency, performance, and emissions of IGCC systems. Specifically, this project will construct and test advanced turbine components including hydrogen combustion components, materials, sensors, and airfoil designs under load conditions.
General Electric Company **FC26-05NT42643.2**	Recovery Act: Advanced Hydrogen Turbine Development—Materials	5	This project will focus on advancing state-of-the-art industrial-frame turbine technology for hydrogen-fueled turbine machinery. Advanced turbine components will improve the efficiency, performance, and emissions of IGCC systems. Specifically, this project will construct and test advanced turbine components including hydrogen combustion components, materials, sensors, and airfoil designs under load conditions.
General Electric Company **FC26-05NT42643.3**	Recovery Act: Advanced Hydrogen Turbine Development—Aerodynamics and Heat Transfer	5	This project will focus on advancing state-of-the-art industrial-frame turbine technology for hydrogen-fueled turbine machinery. Advanced turbine components will improve the efficiency, performance, and emissions of IGCC systems. Specifically, this project will construct and test advanced turbine components including hydrogen combustion components, materials, sensors, and airfoil designs under load conditions.

Table 7. **Advanced Turbines Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Georgia Tech Research Corporation **FE0004555**	Turbulent Flame Propagation Characteristics of High-Hydrogen-Content Fuels	3	This project will improve the understanding of turbulent flame propagation characteristics of high-hydrogen-content (HHC) fuels. Improved knowledge of flame propagation enables predicting combustion dynamics and improved large eddy simulation (LES) capabilities, which will lead to hydrogen combustor designs that produce less emissions at higher heating rates. Specifically, this project will gather data using optical flame emission for mixtures that simulate syngas fuels and systems using exhaust gas recirculation (EGR) that will improve physics-based models of turbulent burning rates.
Georgia Tech Research Corporation **FE0011722**	Microstructure Sensitive Crystal Viscoplasticity for Ni-Base Superalloys	2	This project will develop a microstructure-sensitive crystal viscoplasticity (CVP) model for single-crystal Ni-base superalloys targeted for use in the hot gas path sections of industrial gas turbines. Single-crystal-material models will allow for improved operational guidelines and improved component life that will lead to decreased maintenance costs and reduced costs of electricity. Specifically, this project will develop a microstructure-sensitive (CVP) model that accounts for γ' precipitate morphology evolution that will be introduced through the coupling of coarsening kinetics and constitutive relations of the CVP model followed by conducting long-term creep-fatigue interaction studies on two single-crystal Ni-base superalloys with specific emphasis on the role of microstructure.
Louisiana State University System **FE0004734**	Computational Design and Experimental Validation of New Thermal Barrier Systems	3	This project will utilize a theoretical/computational approach to design a high-performance thermal barrier coating (TBC) with enhanced top and bond coat. Turbine materials research seeks to improve coating materials that will allow for higher temperature operation and increased durability leading to increased turbine efficiency and reduced maintenance. Specifically, this project will use an ab initio (i.e., from first principles) molecular dynamics-based design tool to screen and identify TBC systems with desired physical properties, using high-performance computing (HPC) simulations, to eliminate the need for expensive and time-consuming trial-and-error processes.
NETL-ORD **FWP-2012.03.02.2**	ORD Turbine Thermal Management—Task 2: Aerothermal and Heat Transfer	3	This project will identify the combination of internal and external cooling concepts that provide composite benefit for reduced cooling flow, heat management, and can be commercially manufactured. Turbine aerodynamics and heat transfer research will develop advanced cooling technology that will allow for higher firing temperatures, which translate into increased cycle efficiency. Specifically, this project will investigate NETL-Regional University Alliance's (RUA) near-surface embedded microchannel (NSEMC) concept, porous media TBCs, and/or tripod-hole film cooling configurations for effectiveness and manufacturability.
NETL-ORD **FWP-2012.03.02.3**	ORD Turbine Thermal Management—Task 3: Coating and Materials Development	3	This project will provide an integrated materials composite architecture for use with commercial metal substrate. Turbine materials research seeks to improve coating materials that will allow for higher temperature operation and increased durability leading to increased turbine efficiency and reduced maintenance. Specifically, this project will develop bond coat, diffusion barrier coating, and extreme temperature TBCs to provide composite architecture benefits for maximum temperature, thermal flux, and gas environment compatibility.
NETL-ORD **FWP-2012.03.02.4**	ORD Turbine Thermal Management—Task 4: Design Integration and Testing	3	This project will conduct bench-scale testing of manufacturable aerothermal cooling/coating architecture under realistic conditions to quantify the benefit of cooling and material advances. Turbine aerodynamics and heat transfer research will develop advanced cooling technology that will allow for higher firing temperatures, which translate into increased cycle efficiency. Specifically, this project will work with commercial and small business organizations to manufacture test articles containing appropriate internal microchannel configurations, tripod-hole architectures, and applied coatings for heat transfer assessment at near room temperature and at high temperature under pressurized combustion gas conditions generated in NETL's aerothermal test facility.
NETL-ORD **FWP-2012.03.02.5**	ORD Turbine Thermal Management—Task 5: Secondary Flow Rotating Rig	3	This project will design and construct a world-class test facility for testing new cooling improvement strategies for the turbine rotating blade platform. Turbine aerodynamics and heat transfer research will develop advanced cooling technology that will allow for higher firing temperatures, which translate into increased cycle efficiency. Specifially, this project will build a rotating test rig with the primary focus of increasing turbine efficiencies by using disruptive new designs in sealing the interfaces between stationary and rotating airfoil components, resulting in reductions in fuel usage by an order of magnitude or more.

Table 7. **Advanced Turbines Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
NETL-ORD **FWP-2012.03.02.6**	ORD Turbine Thermal Management—Task 6: Pressure Gain Combustion	2	This project will conduct lab-scale and bench-scale testing of devices that achieve pressure gain combustion as a result of a quasi-steady detonation process. Viable pressure gain combustion has the potential to improve the overall system efficiency when coupled with a turbine. Specifically, this project will upgrade a lab-scale rig to study deflagration to detonation transition and upgrade the high-pressure test rig for rotating detonation combustion operability with natural gas and natural gas/hydrogen blends.
Oak Ridge National Laboratory **FWP-FEAA070**	Coating Issues in Coal-Derived Synthesis Gas/ Hydrogen-Fired Turbines	3	This project will perform three tasks that will help understand the role of water vapor and dopants on TBC lifetime. Turbine materials research seeks to improve coating materials that will allow for higher temperature operation and increased durability leading to increased turbine efficiency and reduced maintenance. Specifically, this project will study the effect of higher water vapor contents on TBC life during thermal cycling, quantify the benefit of adding yttrium (Y) and lanthanum (La) dopants to Ni-base superalloys on TBC lifetime, and characterize the microstructure and microchemistry of these TBC systems to assist in mechanistic understanding of the roles of dopants and water vapor on coating lifetime.
Ohio State University Research Foundation **FE0007156**	Effects of Hot Streak and Phantom Cooling on Heat Transfer in a Cooled Turbine Stage Including Particulate Deposition	3	This project will modify the particulate deposition model developed in prior work to better account for the fundamental physics of particle impact and sticking. Turbine aerodynamics and heat transfer research will develop advanced cooling technology that will allow for higher firing temperatures, which translate into increased cycle efficiency. Specifically, this project will refine the deposition model to include the evolution and migration of hot streaks and the effects of film cooling on hot streaks and deposition, and validate these data using the turbine reacting flow facility.
Purdue University **FE0007099**	Structure and Dynamics of Fuel Jets Injected into a High-Temperature Subsonic Crossflow: High-Data-Rate Laser Diagnostic Investigation	3	This project will develop benchmark quality data sets for high-hydrogen-content fuel reacting jets in crossflow. Validation databases allow hydrogen combustor designers to confirm advanced designs that reduce emissions while operating at higher temperatures. Specifically, this project will use advanced laser diagnostics to probe the flow fields in a high-pressure gas turbine combustion facility to generate the validation database.
Purdue University **FE0011796**	New Mechanistic Models of Creep-Fatigue Interactions for Gas Turbine Components	2	This project will develop novel tools to predict creep-fatigue crack growth in Ni-based gas turbine alloys for stationary power applications. Incorporation of this new model into existing product lifecycle management approaches at NETL has significant potential to reduce turbine manufacturing costs and maintenance costs through increased blade life, leading to lower plant costs and lower electricity costs. Specifically, this project will create and validate a robust, multiscale, mechanism-based model that quantitatively predicts creep-fatigue crack growth and failure in the Ni-based gas turbine alloy IN 718.
Purdue University **FE0011822**	Effects of Exhaust Gas Recirculation on Turbulent Combustion and Emissions in Advanced Gas Turbine Combustors with High-Hydrogen-Content Fuels	2	This project will focus on the impact of EGR when used with HHC fuels. Improving the understanding of hydrogen combustion under these conditions will aid in developing improved combustion technologies that deliver higher temperatures while keeping emissions low. Specifically, this project will develop experimental methods, kinetic models, and numerical tools to quantify and predict the impact of EGR on nitrogen oxides and carbon monoxide emissions, combustion kinetics, radiation heat transfer, turbulent combustion, and combustion instabilities for HHC fuels by using laminar and turbulent flow reactors and gas turbine combustors operating at high temperatures and pressures.
Regents of the University of Michigan **FE0007060**	Development and Experimental Validation of Large Eddy Simulation Techniques—Syngas Combustion	2	This project will focus on the development of a computer model that can predict unstable combustion of HHC fuels. Improving LES models for HHC fuels will lead to hydrogen combustor designs that produce fewer emissions at higher temperatures. Specifically, this project will develop an improved LES model by analyzing critical modeling assumptions and validate the model by conducting high-pressure measurements of HHC fuel combustion in a dual-swirl gas turbine combustor.
Regents of the University of Michigan **FE0007465**	Fundamental Studies to Enable Robust, Reliable, Low-Emission Gas Turbine Combustion of High-Hydrogen-Content Fuels	2	This project will expand the experimental database of HHC combustion kinetic benchmarks. Improving benchmark data for HHC fuels will improve the tools available for hydrogen combustor designs that will produce fewer emissions at higher temperatures. Specifically, this project will conduct Rapid Compression Facility experiments to extend the high-quality, low-uncertainty experimental database of HHC combustion kinetic benchmarks at operating conditions including high pressures, high temperatures, and the effects of dilution with exhaust gases.

Table 7. **Advanced Turbines Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Siemens Energy, Inc. **FC26-05NT42644.1**	Recovery Act: Advanced Hydrogen Turbine Development—Combustion	5	This project will focus on advancing state-of-the-art industrial-frame turbine technology for hydrogen-fueled turbine machinery. Advanced turbine components will improve the efficiency, performance, and emissions of IGCC systems. Specifically, this project will construct and test advanced turbine components including hydrogen combustion components, materials, sensors, and airfoil designs under load conditions.
Siemens Energy, Inc. **FC26-05NT42644.2**	Recovery Act: Advanced Hydrogen Turbine Development—Materials	5	This project will focus on advancing state-of-the-art industrial-frame turbine technology for hydrogen-fueled turbine machinery. Advanced turbine components will improve the efficiency, performance, and emissions of IGCC systems. Specifically, this project will construct and test advanced turbine components including hydrogen combustion components, materials, sensors, and airfoil designs under load conditions.
Siemens Energy, Inc. **FC26-05NT42644.3**	Recovery Act: Advanced Hydrogen Turbine Development—Aerodynamics and Heat Transfer	5	This project will focus on advancing state-of-the-art industrial-frame turbine technology for hydrogen-fueled turbine machinery. Advanced turbine components will improve the efficiency, performance, and emissions of IGCC systems. Specifically, this project will construct and test advanced turbine components including hydrogen combustion components, materials, sensors, and airfoil designs under load conditions.
Tennessee Technological University **FE0007332**	An Alternative Low-Cost Process for Deposition of MCrAlY Bond Coats for Advanced Syngas/Hydrogen Turbine Applications	3	This project will utilize a novel coating process to synthesize a chromium-aluminum-yttrium (MCrAlY; where M = nickel [Ni], cobalt [Co], or a mixture of Ni and Co) bond coat. Turbine materials research seeks to improve coating materials that will allow for higher temperature operation and increased durability leading to increased turbine efficiency and reduced maintenance. Specifically, this project will use electrodeposition to deposit optimally designed MCrAlY bond coats using a sulfur-free electrolyte and analyze the process and resulting bond coats for effects on composition and microstructure.
Texas Engineering Experiment Station **FE0011778**	High-Pressure Turbulent Flame Speeds and Chemical Kinetics of Syngas Blends with and without Impurities	2	This project will improve the understanding of how turbulent flame speeds vary for HHC fuel blends. Understanding turbulent flame speeds of HHC fuels in the presence of likely contaminates allows hydrogen combustor designs that produce fewer emissions at higher temperatures. Specifically, this project will utilize both flame speed and shock tubes test facilities to obtain fundamental combustion data relevant for chemical kinetics modeling to assess the impact of likely impurities and validate kinetics submechanisms for each impurity at realistic ranges of mixture composition, stoichiometry, and pressure.
The Research Foundation of State University of New York **FE0004771**	Advanced Thermal Barrier Coatings for Operation in High-Hydrogen-Content-Fueled Gas Turbines	3	This project will improve science-based understanding of TBCs to create a pathway for reliable IGCC coating development. Turbine materials research seeks to improve coating materials that will allow for higher temperature operation and increased durability leading to increased turbine efficiency and reduced maintenance. Specifically, this project will develop TBCs through investigation into how processing affects the oxidation behavior of metallic bond coats in water vapor environments and by developing ceramic top coat architectures using thermal spray processing of emerging zirconate materials that have shown promise as advanced thermal barriers.
University of California, Irvine **FE0007045**	Development of Criteria for Flameholding Tendencies within Premixer Passages for High-Hydrogen-Content Fuels	3	This project will focus on evaluating flameholding tendencies of various combustor premixer geometric features using HHC fuels. The development of design guides that accurately infer when flameholding will occur will lead to hydrogen combustor designs that produce fewer emissions at higher temperatures. Specifically, this project will evaluate flameholding of various fuels at high temperatures and pressures that are relevant to actual turbine conditions.
University of California, Irvine **FE0011929**	Abradable Sealing Materials for Emerging IGCC-Based Turbine System	2	This project will provide an improved mechanistic understanding of factors governing the performance of high-temperature abradable seals and degradation mechanisms unique to coal-derived syngas and HHC-based combustion environments. This improved knowledge will result in better seal design, reduced leakage, and reduced costs through increased performance and efficiency. Specifically, this project will investigate several classes of abradable coatings (including metal and ceramic-based systems currently being utilized) under simulated exposures to syngas-based combustion environments to determine their relevant wear/abrasive recession behavior, hardness, stability under cyclic oxidation, and general thermomechanical behavior.

Table 7. **Advanced Turbines Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
University of California, Irvine **FE0011948**	Development of Criteria for Flashback Propensity in Jet Flames for High-Hydrogen-Content and Natural Gas Type Fuels	2	This project will develop design guides to predict flame flashback propensity for high-hydrogen-content fuels. A better fundamental understanding of flashback tendencies and will also provide insight into strategies for preventing flashback when designing hydrogen combustors that operate with fewer emissions at higher temperatures. Specifically, this project will conduct experimental studies of jet flame flashback using a test facility designed to investigate flashback at gas turbine relevant conditions and correlating the results to local flow and injector tip conditions.
University of Connecticut **FE0007382**	Low-Thermal-Conductivity, High-Durability Thermal Barrier Coatings for IGCC Environments	3	This project will use a novel solution precursor plasma spray (SPPS) process to deposit TBCs. Turbine materials research seeks to improve coating materials that will allow for higher temperature operation and increased durability leading to increased turbine efficiency and reduced maintenance. Specifically, this project will determine the depostion parameters to use with SPPS, use them to apply a TBC with unique microstructure that will have high thermal conductivity with reduced rare earth metals, and analyze the resulting coatings for durability.
University of North Dakota **FE0004588**	Environmental Considerations and Cooling Strategies for Vane Leading Edges in a Syngas Environment	3	This project will study technologies important to the reliability of high-hydrogen-fueled gas turbines. Advanced cooling technology will allow for higher firing temperatures, which translate into increased cycle efficiency. Specifically, this project will utilize data from Ohio State University's turbine reacting flow rig (TuRFR) facility to study turbulence approaching turbine vanes, the influences of varying levels of turbulence on deposition rates, and the combined influence of turbulence and realistic roughness on film cooling effectiveness and surface heat transfer.
University of North Dakota **FE0007325**	Preparation and Testing of Corrosion- and Spallation-Resistant Coatings	3	This project is designed to refine the evaporative metal bonding method and determine if it results in increased lifetimes. Turbine materials research seeks to improve coating materials that will allow for higher temperature operation and increased durability leading to increased turbine efficiency and reduced maintenance. Specifically, this project will measure the diffusion rates of zinc, design heat treatments for bonding to CM247LC and Rene 80 superalloys, bond the corrosion and spallation-resistant alloy to the substrates, and test them to determine if the improved process and modeling increases part lifetimes.
University of North Dakota **FE0011875**	Thermally Effective and Efficient Cooling Technologies for Advanced Gas Turbines	2	This project will research three cooling methods for improved turbine airfoil cooling performance. Turbine aerodynamics and heat transfer research will develop advanced cooling technology that will allow for higher firing temperatures, which translate into increased cycle efficiency. Specifically, this project will investigate incremental impingement for the leading edge, counter cooling for the pressure and suction surfaces, and sequential impingement for the pressure and suction surfaces of the vane.
University of Pittsburgh **FE0007271**	Degradation of TBC Systems in Environments Relevant to Advanced Gas Turbines for IGCC Systems	3	This project will utilize high-temperature corrosion testing facilities to determine the degradation mechanisms of current state-of-the-art TBC in simulated syngas environments. Turbine materials research seeks to improve coating materials that will allow for higher temperature operation and increased durability leading to increased turbine efficiency and reduced maintenance. Specifically, this project will investigate how the interaction between the ash and oxidants affect TBC degradation through enhanced attack of yttria-stabilized zirconia (YSZ) top coating by chemical reaction, physical damage of the topcoat by molten deposit penetration, and accelerated bond coat corrosion.
University of South Carolina **FE0012005**	An Experimental and Modeling Study of NO_x-Carbon Monoxide Formation in High-Hydrogen-Content Fuels Combustion in Gas Turbine Applications	2	This project will focus on improving the ability to predict the formation of NO_x when using high-hydrogen-content fuels. Understanding NO_x formation pathways will allow hydrogen combustor designers to reduce emissions while operating at higher temperatures. Specifically, a kinetic model will be developed and validated via data obtained from a high-pressure combustion system and a high-pressure laminar flow reactor, and then incorporated into a computational fluid dynamics model as both detailed and reduced models and also through a dynamic on-the-fly mechanism reduction approach.
University of Texas at Austin **FE0005540**	Improving Durability of Turbine Components Through Trenched Film Cooling and Contoured Endwalls	3	This project will utilize wind tunnel facilities to simulate film cooling of turbine vanes, blades, and endwalls using molten wax. Turbine aerodynamics and heat transfer research will develop advanced cooling technology that will allow for higher firing temperatures, which translate into increased cycle efficiency. Specifically, this project will analyze the wax particle depostion for shallow trench cooling configurations of a simulated vane and various endwall cooling configurations using infrared thermography.

Table 7. **Advanced Turbines Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
University of Texas at Austin **FE0007107**	Large Eddy Simulation Modeling of Flashback and Flame Stabilization in Hydrogen-Rich Gas Turbines Using a Hierarchical Validation Approach	2	This project will focus on the development of a computer model that can simulate combustion of HHC fuels. Improving LES models for HHC fuels will lead to hydrogen combustor designs that produce fewer emissions at higher temperatures. Specifically, this project will develop an LES model using direct numerical simulation (DNS), conduct targeted experimental studies to produce high-quality data under engine-relevant conditions to validate the models, and transfer the validated models to industry.
University of Texas at Austin **FE0012053**	Predictive Large Eddy Simulation Modeling and Validation of Turbulent Flames and Flashback in Hydrogen-Enriched Gas Turbines	2	This project will focus on the development of a computational model that can capture flame flashback and propagation for combustion of HHC fuels. Improving LES models for HHC fuels will lead to hydrogen combustor designs that produce fewer emissions at higher temperatures. Specifically, this project will construct a moderate-pressure turbulent stratified burner test facility to validate the predictive model with correlations between mixture fraction and velocity and flame front geometry over a wide range of turbine-relevant conditions.
Virginia Polytechnic Institute and State University **FE0011762**	Evaluation of Flow and Heat Transfer Inside Lean Pre-Mixed Combustor Systems Under Reacting Flow Conditions	2	This project will provide a better understanding of combustor swirling flow and its effect on combustor liner surface heat transfer. This will support the development of more effective cooling schemes to maintain and improve combustor durability, leading to reduced maintenance costs for turbine operators. Specifically, this project will focus on how the hot swirling gases interact with the liner wall of a gas turbine combustor to provide insight into the effect of swirl nozzle exit flows and the mixing characteristics of fuel/air and its impingement on liner and dome regions and support the development of more effective cooling schemes.
Key Technology—Supercritical CO_2 Power Cycles			
National Institute of Standards and Technology **FE0003931**	Thermophysical Properties of CO_2 and CO_2-Rich Mixtures	2	This project will contribute to program goals by expanding supercritical CO_2 data to aid modeling efforts. This effort will improve the quality of the thermodynamic data on CO_2 over the range of conditions of interest in the design and development of supercritical CO_2 power cycles. Specifically, this project will execute experimental and modeling work on the thermodynamics of CO_2/water mixture systems, modeling work on the viscosity of pure CO_2, and experimental and modeling work on the thermal conductivity of pure CO_2.
Oak Ridge National Laboratory **FWP-FEAA112**	Materials Issues in Supercritical Carbon Dioxide	3	This project will establish a broad understanding of the materials issues associated with scaling up supercritical CO_2 systems to higher temperatures. These higher temperatures will increase the efficiency of commercial power production. Specifically, this project will build and validate a materials testing rig and test corrosion mechanisms in supercritical CO_2 as a function of temperature and establish temperature limits for various classes of materials (e.g., ferritic and austenitic steels, Ni-base alloys, and alumina-forming alloys) for supercritical CO_2 systems.

ADVANCED ENERGY SYSTEMS

COAL AND COAL-BIOMASS TO LIQUIDS

The Coal and Coal-Biomass to Liquids (CCBTL) program supports the development of technologies that will enable the production of liquid transportation fuels, from domestic coal or coal-biomass blends, such that (1) the products are cost-competitive with those from conventional petroleum-based liquid fuels production, and (2) the processes have GHG emissions that are less than or equal to those for conventional petroleum refining. The CCBTL program works closely with the Gasification Systems program to coordinate R&D efforts and ensure that technology development is conducted efficiently.

The CCBTL program is focused on two key technologies to reduce the cost and increase the efficiency of producing liquid fuels from coal and biomass while simultaneously minimizing GHG emissions. These two key technologies are Advanced Fuels Synthesis and Coal-Biomass Feed and Gasification.

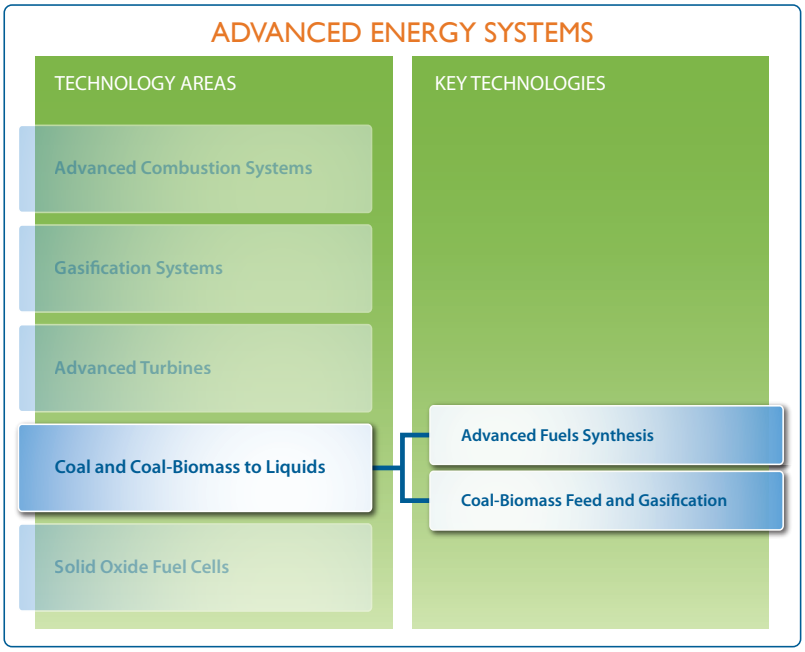


Figure 12. Coal and Coal-Biomass to Liquids Key Technologies

Targets

The CCBTL Technology Area supports the achievement of GPRA Endpoint Performance Target 2—*Advanced Energy Systems with CO_2 capture at no more than $40 per tonne of CO_2 captured by 2020.*

Benefits

Liquid transportation fuels such as gasoline, diesel fuel, and jet fuel are conventionally produced from petroleum. However, the rising cost of oil, its volatile pricing history, and concerns over its supply and sourcing have revived interest in synthesis of liquid fuels from coal and coal-biomass mixtures. Being able to cost-effectively use domestic coal and biomass to create transportation fuels, and considering the great extent of domestic coal reserves in the United States, would significantly increase U.S. energy security and could act to stabilize pump prices against global spikes or trends in the cost per barrel of oil.

Critical Challenges

Research and development work being done as part of the CCBTL program is expected to reduce the cost of liquids transportation fuel production from coal and biomass with carbon emission control. These include:

- Developing advanced process systems that will improve the performance and reduce the cost of technologies producing liquid fuels from syngas.
- Developing and validating mathematical models that accurately predict the composition of syngas produced when coal and biomass are gasified together in the same reactor to provide more accurate predictions of transportation liquids from the syngas.
- Developing technologies to reliably deliver biomass and coal-biomass mixtures to a gasifier reliably.

Projects Assessed

The TRLs of 10 projects were assessed in the CCBTL Technology Area: 5 in Advanced Fuels Synthesis and 5 in Coal-Biomass Feed and Gasification. This collective body of work is being pursued to expand the state of knowledge and strengthen the technical basis for the ongoing and planned research in this area.

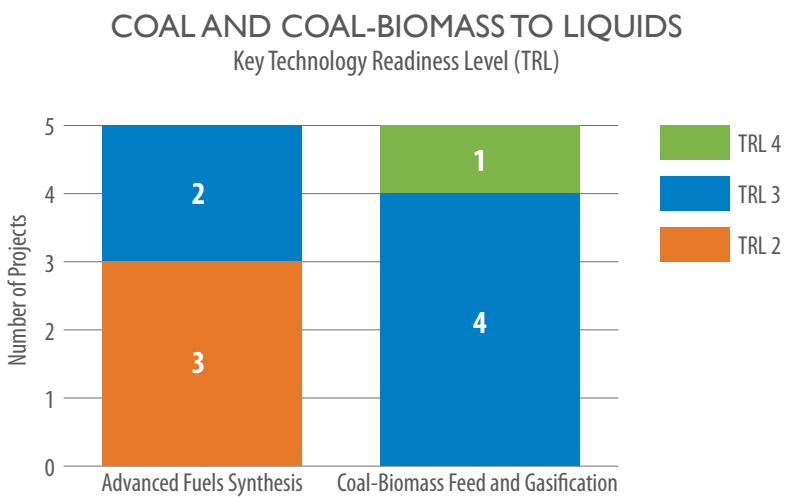


Figure 13. TRL Scores for Coal and Coal-Biomass to Liquids Projects

Rating Summary

The critical technology challenges related to CCBTL require a portfolio of technologies encompassing the two key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the CCBTL technology emerges as a range of TRL values. The overall readiness of the CCBTL Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 2 to 4.

Technology Readiness Level Range for Coal and Coal-Biomass to Liquids

2–4

COAL AND COAL-BIOMASS TO LIQUIDS

KEY TECHNOLOGIES

ADVANCED FUELS SYNTHESIS

This key technology focuses on catalyst and reactor optimization to reduce the cost of producing liquid transportation fuels from coal-biomass mixtures. This also includes hybrid concepts, for instance, combining indirect coal liquefaction with direct coal liquefaction for a more valuable product slate, or using natural gas as a hydrogen source for fuel upgrading. It supports the development and demonstration of advanced separation technologies, and sponsors research on novel technologies for liquid fuels synthesis and for characterization of the range of products and product quality.

5 PROJECTS
2–3 TRL RANGE

Five projects within the Advanced Energy Systems Coal and Coal-Biomass to Liquids portfolio focused on improving advanced fuels synthesis technologies were assessed. The current TRL of this key technology spans a range of 2–3 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

COAL-BIOMASS FEED AND GASIFICATION

This key technology focuses on being able to cost-effectively use biomass to reduce the GHG impact of a coal-to-liquids plant. There are limited operational experience and experimental data on feeding coal and biomass to the same reactor, and there are numerous technical issues that need to be resolved. The CCBTL program is supporting projects to better understand the reactive properties of coal-biomass mixed fuels, characterize the products from gasifying coal-biomass mixtures, develop technologies to advantageously process biomass, and determine the effect of biomass contaminants on Fischer-Tropsch (F-T) processes. This key technology is advancing scientific knowledge of the production of liquid hydrocarbon fuels from coal and/or coal-biomass mixtures. Activities support research for handling and processing of coal-biomass mixtures, ensuring those mixtures are compatible with feed delivery systems, identifying potential impacts on downstream components, and gasifier optimization.

5 PROJECTS

3–4 TRL RANGE

Five projects within the Advanced Energy Systems Coal and Coal-Biomass to Liquids portfolio focused on improving coal-biomass feed and gasification technologies were assessed. The current TRL of this key technology spans a range of 3–4 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

COAL AND COAL-BIOMASS TO LIQUIDS

PORTFOLIO

Table 8. **Coal and Coal-Biomass to Liquids Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Advanced Fuels Synthesis			
Altex Technologies Corporation **FE0010427**	Laboratory-Scale Liquids Production and Assessment: Coal and Biomass to Drop-In Fuels	3	This Altex Technologies Corporation project will develop and test an integrated laboratory-scale coal-and-biomass-to-liquids system (CBTL). The impact of this project will be to develop a cost-effective gasification-based CBTL process to produce renewable liquid fuels that will provide diversity of fuel supply and energy security while resulting in lower future capital and operating costs. Specifically, this project will design and build (1) an innovative upstream process that converts the solid feed into a highly reactive intermediate and (2) a downstream process that converts the intermediate product into liquid fuel using a low-temperature catalytic system.
NETL-ORD **FWP-2012.03.05.2**	ORD NETL-RUA Fuels FWP—Task 2: Materials Development	2	This NETL Office of Research and Development (ORD) project will determine the effectiveness of protective coatings and modified coatings on corrosion prevention and performance lifetime of hydrogen-separation materials. The impact of this project will be to develop a cost-effective gasification-based CBTL process to produce renewable liquid fuels that will provide diversity of fuel supply and energy security while resulting in lower future capital and operating costs. Specifically, this project will study various formulations of hydrogen-separation alloys and light gas conversion catalysts focusing on coking and lifetime issues.
NETL-ORD **FWP-2012.03.05.3**	ORD NETL-RUA Fuels FWP—Task 3: Process Development	2	This NETL ORD project will evaluate various configurations of process models for methane-to-benzene conversions. The impact of this project will be to develop a cost-effective gasification-based CBTL process to produce renewable liquid fuels that will provide diversity of fuel supply and energy security while resulting in lower future capital and operating costs. Specifically, this project will collect laboratory data to validate the models developed for the process.
NETL-ORD **FWP-2012.03.05.4**	ORD NETL-RUA Fuels FWP—Task 4: Performance Validation	2	This NETL ORD will explore the performance of H_2-enrichment membranes at process-relevant conditions as well as evaluate the chemical composition and applicability of products generated. The impact of this project will be to develop a cost-effective gasification-based CBTL process to produce renewable liquid fuels that will provide diversity of fuel supply and energy security while resulting in lower future capital and operating costs. Specifically, this project will provide compositional and performance analysis of chemicals, intermediates, and finished fuels generated by analytical tests conducted in a laboratory setting to validate performance of conversion materials.

Table 8. **Coal and Coal-Biomass to Liquids Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Southern Research Institute **FE0010231**	Small-Scale Coal-Biomass Liquids Production Using Highly Selective Fischer-Tropsch Catalyst	3	This Southern Research Institute project will (1) demonstrate the potential for CBTL cost reduction by maximizing the production of C5-C20 hydrocarbon liquids using a selective F-T synthesis catalyst and (2) evaluate the impacts of the addition of biomass to coal on product characteristics, carbon footprint, and economics. The impact of this project will be to develop a cost-effective gasification-based CBTL process to produce renewable liquid fuels that will provide diversity of fuel supply and energy security while resulting in lower future capital and operating costs. Specifically, this project will design, build, and test a novel bench-scale reactor system for conversion of coal-biomass feedstocks to gasoline- and diesel-range hydrocarbon liquids using the F-T process chemistry using a syngas slipstream from the pilot-scale gasifier at NCCC with a novel Chevron F-T catalyst.
Key Technology—Coal-Biomass Feed and Gasification			
CoalTek, Inc. **FE0005293**	Development of Biomass-Infused Coal Briquettes for Co-Gasification	4	This CoalTek, Inc., project will demonstrate the use of a microwave process that combines coal and biomass to produce a suitable single-stream feedstock pellet for co-gasification. The impact of this project will be to develop a cost-effective gasification-based CBTL process to produce renewable liquid fuels that will provide diversity of fuel supply and energy security while resulting in lower future capital and operating costs. Specifically, this project will focus on (1) microwave processing of batch-scale production and laboratory characterizations of briquette formulations to determine the most suitable briquetted product for co-gasification; (2) use a larger scale, continuous process to demonstrate the performance of the co-briquetted fuels during co-gasification in two different pilot-plant designs, and (3) enable realistic cost estimates of a commercial-scale microwave process as a part of a CBTL system.
Gas Technology Institute **FE0005349**	R&D to Prepare and Characterize Robust Coal-Biomass Mixtures for Direct Co-Feeding into Gasification	3	This Gas Technology Institute project will develop biomass from loblolly pine, to a densified coal-like product suitable for fuel in a CBTL process. The impact of this project will be to develop a cost-effective gasification-based CBTL process to produce renewable liquid fuels that will provide diversity of fuel supply and energy security while resulting in lower future capital and operating costs. Specifically, this project will deconstruct the lignocellulosic feedstock using hydrothermal carbonization (HTC) to produce samples for property testing; from the characteristic data, simulations will be conducted to perform techno-economic analysis to evaluate the viability of HTC for producing a new coal/HTC biomass fuel.
Georgia Tech Research Corporation **FE0005339**	Development of Kinetics and Mathematical Models for High-Pressure Gasification of Lignite-Switchgrass Blends	3	This Georgia Tech Research Corporation project will use an experimental reactor to produce data and develop kinetic rate expressions for pyrolysis and char gasification for coal-biomass blends. The impact of this project will be to develop a cost-effective gasification-based CBTL process to produce renewable liquid fuels that will provide diversity of fuel supply and energy security while resulting in lower future capital and operating costs. Specifically, this project will evaluate the effect of pyrolysis conditions on the porous char structure to build mathematical models that combine true kinetic rate expressions with transport models for predicting gasification behavior for a broad range of pressures and temperatures, and to investigate the physical and chemical parameters that might lead to synergistic effects in coal-biomass blends gasification.
Virginia Polytechnic Institute and State University **FE0005451**	Advanced Systems: Preprocessing and Characterizing Coal-Biomass Mixtures as Next-Generation Fuels and Feedstocks	3	This Virginia Polytechnic Institute and State University project will develop an engineered system for manufacturing coal-biomass briquettes or pellets containing 10–30 percent biomass for direct co-feeding into industrial gasifiers. The impact of this project will be to develop a cost-effective gasification-based CBTL process to produce renewable liquid fuels that will provide diversity of fuel supply and energy security while resulting in lower future capital and operating costs. Specifically, this project will determine the key reactive properties for coal-biomass mixed fuels testing sub-bituminous coal mixed with biomass feedstocks of hybrid poplar wood, switchgrass, or corn stover utilizing as necessary novel binding additives and an advanced conditioning process for upstream sizing, upgrading, and drying.
Virginia Polytechnic Institute and State University **FE0005476**	Investigation of Coal-Biomass Catalytic Gasification Using Experiments, Reaction Kinetics and Computational Fluid Dynamics	3	This Virginia Polytechnic Institute and State University project will use experimental reactor data to develop kinetic rate expressions for pyrolysis and char gasification for the coal-biomass blends under conditions free from transport limitations to develop a detailed understanding of the effect of pyrolysis conditions on the porous char structure. The impact of this project will be to develop a cost-effective gasification-based CBTL process to produce renewable liquid fuels that will provide diversity of fuel supply and energy security while resulting in lower future capital and operating costs. Specifically, this project will build mathematical models that combine true kinetic rate expressions with transport models for predicting gasification behavior for a broad range of pressures and temperatures, and investigate the physical and chemical parameters that might lead to synergistic effects in coal-biomass blends gasification.

ADVANCED ENERGY SYSTEMS

SOLID OXIDE FUEL CELLS

Solid oxide fuel cells (SOFCs) are electrochemical devices that convert chemical energy of a fuel and oxidant directly into electrical energy. Since SOFCs produce electricity through an electrochemical reaction and not through a combustion process, they are much more efficient and environmentally benign than conventional electric power-generation processes. Their inherent characteristics make them uniquely suitable to address the environmental, climate change, and water concerns associated with fossil-fuel-based electric power generation. The Solid Oxide Fuel Cells program maintains a diversified portfolio of near-, mid-, and long-term RD&D projects, ranging from laboratory-scale experiments to proof-of-concept system demonstrations. These projects will foster the advancement of SOFC technology for low-cost, highly efficient SOFC power-generation systems that produce electric power from natural gas or coal with carbon capture capabilities.

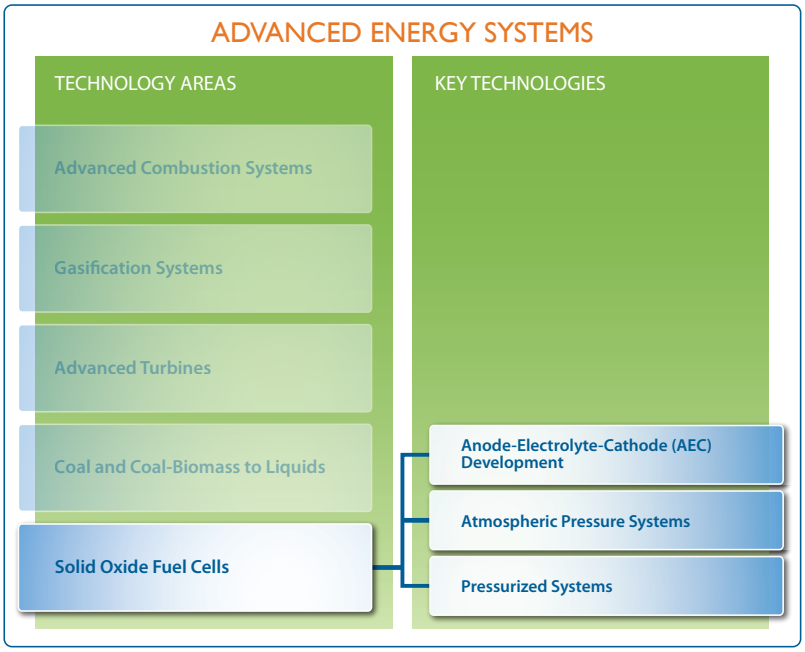


Figure 14. Solid Oxide Fuel Cells Key Technologies

Targets

The Solid Oxide Fuel Cells Technology Area supports the achievement of GPRA Endpoint Performance Target 2—*Advanced Energy Systems with CO_2 capture at no more than $40 per tonne of CO_2 captured by 2020.*

Benefits

The integration of SOFC technology with advanced gasification systems and other advanced technologies being pursued by the companion programs within Advanced Energy Systems results in an integrated gasification fuel cell (IGFC) power system that will meet or exceed the goals of the Advanced Energy Systems program. IGFC power systems are projected to achieve greater than 95 percent carbon capture, efficiencies greater than or equal to 60 percent (higher heating value), have near-zero emissions of critical pollutants, and dramatically reduce raw water consumption while producing electric power at a COE competitive with current technology without carbon capture and storage.

Critical Challenges

The critical challenges facing the Solid Oxide Fuel Cells Technology Area cover a spectrum of issues, ranging from developing a better understanding of the fundamental reaction kinetics of the cathode oxygen reduction mechanism to acquiring operational experience in SOFC power systems:

- Cells—challenges at the cell level include improving electrochemical performance, reducing long-term degradation rates, improving mechanical integrity, and reducing material and manufacturing costs.
- Stacks—issues include effective reactant flow distribution, thermal management, seals, mechanical integrity, understanding stack failure mechanisms, scaleup, thermally self-sustaining operation, and reducing cost.
- Systems—areas of importance include reducing the cost of high-temperature components, defining the operating envelope, integrating components and subsystems, scale-up to fully integrated power systems, and acquiring operational experience.

Projects Assessed

The TRLs of 18 projects were assessed in the Solid Oxide Fuel Cells Technology Area: 14 in AEC Development, 2 in Atmospheric Pressure Systems, and 2 in Pressurized Systems. This collective body of work is being pursued to expand the state of knowledge and strengthen the technical basis for the ongoing and planned research in this area.

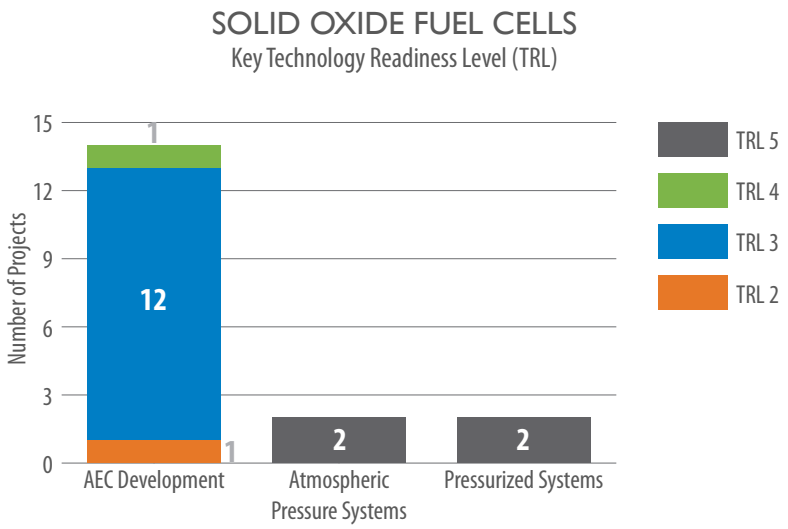


Figure 15. TRL Scores for Solid Oxide Fuel Cells Projects

Rating Summary

The critical technology challenges related to SOFCs require a portfolio of technologies encompassing the three key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the SOFC technology emerges as a range of TRL values. The overall readiness of the Solid Oxide Fuel Cells Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 2 to 5.

Technology Readiness Level Range for Solid Oxide Fuel Cells

2–5

SOLID OXIDE FUEL CELLS

KEY TECHNOLOGIES

ANODE-ELECTROLYTE-CATHODE DEVELOPMENT

14 PROJECTS
2–4 TRL RANGE

A solid oxide fuel cell consists of three components: an anode (fuel electrode), a cathode (air electrode), and an electrolyte that separates the two electrodes. Overall cell performance is determined by the individual and collective performance of these three components. The AEC Development key technology—comprising research at universities, national laboratories, small businesses, and other R&D organizations—consists of projects that will lead to substantially improved cell performance and power density and more reliable and robust systems. Research is focused on the technologies critical to the commercialization of SOFC technology, such as cathode performance, gas seals, interconnects, failure analysis, coal contaminants, fuel processing, and balance-of-plant components. Other research activities evaluate the viability and benefits of advanced cell and stack concepts (including alternative anodes, cathodes, electrolytes, materials, and configurations), advanced processing techniques, and novel fuel cell power systems.

Fourteen projects within the Advanced Energy Systems Solid Oxide Fuel Cells portfolio focused on anode-electrolyte-cathode development were assessed. The current TRL of this key technology spans a range of 2–4 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

ATMOSPHERIC PRESSURE SYSTEMS

2 PROJECTS
5 TRL RANGE

This key technology focuses on the design, scaleup, and integration of the SOFC technology ultimately resulting in fuel cell modules suitable to serve as the building blocks for commercial-scale atmospheric pressure SOFC power systems. Industry Teams are independently developing unique and proprietary SOFC technology suitable for deployment for either syngas- or natural-gas-fueled central station and/or distributed generation applications. They are responsible for the design and manufacture of the fuel cells, hardware development, manufacturing process development, commercialization of the technology, and market penetration. These teams focus on the scaleup of cells and stacks for aggregation into fuel cell modules and the validation of technology that evolves from the AEC Development key technology. Laboratory-scale stack tests, proof-of-concept systems, pilot-scale demonstrations, and deployment of commercial power systems are the responsibility of the Industry Teams. Activities 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.

Two projects within the Advanced Energy Systems Solid Oxide Fuel Cells portfolio focused on improving atmospheric pressure system technologies were assessed. The current TRL of this key technology is 5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

PRESSURIZED SYSTEMS

2 PROJECTS
5 TRL RANGE

SOFCs demonstrate enhanced performance by increasing the cell pressure. Thus, 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. Research activities in the Pressurized Systems key technology are developing a deeper understanding on the behavior of the state-of-the-art SOFC material set under pressurized operation; quantifying the effects of pressure on cell performance, reliability, and degradation; and identifying and resolving the operational issues associated with pressurizing the SOFC stack.

Additionally, this key technology focuses on the design, scaleup, and integration of pressurized SOFC technology ultimately resulting in fuel cell modules suitable to serve as the building blocks for commercial-scale pressurized SOFC power systems. Industry Teams are independently developing unique and proprietary SOFC technology suitable for deployment for either syngas- or natural-gas-fueled central station and/or distributed generation applications. They are responsible for the design and manufacture of the fuel cells, hardware development, manufacturing process development, commercialization of the technology, and market penetration. These teams focus on the scaleup of cells and stacks for aggregation into fuel cell modules and the validation of technology that evolves from the AEC Development key technology. Laboratory-scale stack tests, proof-of-concept systems, pilot-scale demonstrations, and deployment of commercial power systems are the responsibility of the Industry Teams. Activities 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.

Two projects within the Advanced Energy Systems Solid Oxide Fuel Cells portfolio focused on improving pressurized system technologies were assessed. The current TRL of this key technology is 5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

SOLID OXIDE FUEL CELLS

PORTFOLIO

Table 9. **Solid Oxide Fuel Cells Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Anode-Electrolyte-Cathode Development			
Argonne National Laboratory **FWP-49071**	Solid Oxide Fuel Cell Research and Development	3	This project focuses on developing an understanding of cathode surface phenomena to enable the development of models for the design of high-performance cathode materials. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will measure the atomic and chemical state of cathode materials under typical operating conditions, correlate these measurements with ex-situ results, and develop cathode modifications that will accelerate the oxidation reduction reaction and oxygen transport to the electrolyte.
Georgia Tech Research Corporation **FE0009652**	Fundamental Investigators and Rational Design of Durable, High-Performance Cathode Materials	3	This project focuses on characterizing the degradation mechanism of lanthanum strontium cobalt ferrite (LSCF) cathodes under realistic operating conditions, aiming to establish the scientific basis for the design of new materials and electrode structures to mitigate stability issues. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will characterize and correlate the microstructure, morphology, and chemistry behavior of LSCF cathodes with their electrochemical behavior under realistic operating conditions and suggest new cathode materials through modeling and simulation.
Leland Stanford Junior University **FE0009620**	Surface-Modified Electrodes: Enhancing Performance Guided by In Situ Spectroscopy and Microscopy	3	This project focuses on improving cathode activity by directly modifying the chemistry and structure of the nanoscale oxygen reduction reaction (ORR) active surface sites. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will identify the characteristics of active ORR sites that display high electrochemical activity, use this knowledge to engineer electrode surfaces, and optimize and validate the modification strategies.
NETL-ORD **FWP-2012.03.04.2**	ORD NETL-RUA Fuel Cells Initiative—Task 2: Cell and Stack Degradation	3	This project focuses on the investigation of degradation modes exhibited by the AEC, the development of computational models describing the degradation rates, and generation of a modeling tool predicting long-term AEC degradation response. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will conduct cell tests, utilize conventional electrochemical techniques to measure performance, and employ advanced spectroscopic techniques in post-test analysis.
NETL-ORD **FWP-2012.03.04.3**	ORD NETL-RUA Fuel Cells Initiative—Task 3: Electrode Engineering	3	This project focuses on the development and performance evaluation of electrode materials and structure that improve peak cell power output while maintaining cost and durability metrics. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will identify and characterize manufacturing processes, select and evaluate candidate materials, conduct lab-scale performance and stability tests, and demonstrate the preferred process and materials in short-stack testing.
NETL-ORD **FWP-2012.03.04.5**	ORD NETL-RUA Fuel Cells Initiative—Task 5: System Level Economic and Process Models	2	This project focuses on estimating component and system costs and the economic benefits of technical innovations. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will estimate the economic benefits associated with the fundamental and applied research completed in other program-sponsored R&D projects.
Oak Ridge National Laboratory **FWP-FEAA066**	Reliability of Materials and Components for Solid Oxide Fuel Cells	3	This project focuses on identifying and characterizing the mechanisms responsible for the failure of materials, components, and stacks and developing engineered self-healing seal systems. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, the project will conduct lab-scale tests, develop a high-fidelity model to assess and predict behavior, performance, life, and reliability and develop and evaluate self-healing seal designs.

Table 9. **Solid Oxide Fuel Cells Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Pacific Northwest National Laboratory **FWP-40552**	SECA [Solid State Energy Conversion Alliance] Core Technology Program—PNNL	4	This project focuses on developing and evaluating advanced cell and stack components and computational tools and capabilities for cell and stack design analysis and optimization. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will develop, manufacture, and evaluate advanced component materials, manufacturing processes, and computational tools.
Trustees of Boston University **FE0009656**	Unraveling the Role of Transport, Electrocatalysis, and Surface Science in the Solid Oxide Fuel Cell Cathode Oxygen Reduction Reaction	3	This project focuses on improving cell power density and reducing the cell degradation rate by developing newer cathode and electrocatalyst materials. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will employ a combination of experimental and computational tools to probe the surface composition and oxidations states, measure surface exchange and diffusion coefficients of cathode materials, use experimental and theoretical research on thin film cathodes to narrow the choice of newer cathode materials and composition, fabricate and test single cells using selected cathode materials and composition, characterize the microstructure of the cells, and optimize materials choice and cathode microstructure.
University of Connecticut **FE0009682**	Study of the Durability of Doped Lanthanum Manganite- and Cobaltite-Based Cathode Materials Under Real World Air Exposure Atmosphere	3	This project focuses on developing an understanding of the electrical, chemical, and physical processes responsible for cathode degradation under real world air atmosphere exposure conditions. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will study the role of electrode polarization and exposure conditions on cell performance degradation, examine the role of electrode poisoning in the presence of chromium (Cr) vapor, and use computational tools to theoretically deduce cathode degradation mechanisms due to air contaminants.
University of Maryland **FE0009084**	Mechanistic Enhancement of SOFC Cathode Durability	3	This project focuses on investigating the effects of contaminants on cathode degradation mechanisms in order to establish cathode composition and structures and operational conditions to enhance cathode durability. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will determine the mechanistic effects of H_2O and Cr vapor, CO_2, and particulates on cathode durability, quantify microstructural and compositional changes, and determine the surface exchange mechanisms and coefficients using in situ isotope exchange of labeled contaminants.
University of Wisconsin System **FE0009435**	Enhancement of Solid Oxide Fuel Cell Cathode Electrochemical Performance Using Multiphase Interfaces	3	This project focuses on advancing the fundamental understanding of how cathodes operate, centering on the role of material interfaces in determining electrochemical performance. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will determine new operation mechanisms and material architectures using advanced physical and electrochemical characterization techniques and tools.
West Virginia University **FG02-06ER46299**	Direct Utilization of Coal Syngas in High-Temperature Fuel Cells	3	This project focuses on characterizing the effects of impurities found in syngas, developing a model to predict SOFC life when operating on syngas, and developing contaminant-resistant anode materials. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will conduct accelerated anode exposure tests to syngas contaminants, build a model based on the experimental data to predict the lifetime of the anode operating on syngas, and design and develop alternative anode components that are contaminant tolerant.
West Virginia University Research Corporation **FE0009675**	Understanding of Oxygen Reduction and Reaction Behavior and Developing High-Performance and Stable Heterostructured Cathode with Heterostructured Surface	3	This project focuses on developing a better understanding of the fundamental mechanisms of ORRs through experimental investigation and modeling. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will utilize electrical conductivity relaxation to characterize oxygen transport behavior.

Table 9. **Solid Oxide Fuel Cells Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Atmospheric Pressure Systems			
Delphi Automotive Systems, LLC **FE0011769**	Solid Oxide Fuel Cell Power System Development	5	This project focuses on developing cell, stack, and system technology with improved performance, durability, and reliability. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will confirm improvements through component tests, stack tests, and a thermally self-sustaining system test.
FuelCell Energy, Inc. **FE0011691**	SOFC Systems with Improved Reliability and Endurance	5	This project focuses on cell and stack materials and designs, balance-of-plant improvements to extend stack life and limit degradation, and performance evaluation under operating conditions and fuel compositions anticipated for commercially deployed systems. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will design, fabricate, install, and operate a 50 kWe proof-of-concept SOFC module power plant.
Key Technology—Pressurized Systems			
LG Fuel Cell Systems, Inc. **FE0012077**	SECA Coal-Based Systems	5	This project focuses on development and testing of pressurized cells and stacks to advance and validate performance, reliability, robustness, and endurance. Improved cell/stack life and performance will reduce operating cost and increase efficiency, resulting in reduction in the COE and reduction of CO_2 emissions from the entire platform. Specifically, this project will conduct subscale durability tests of single cells, 5-cell and bundle test articles, and a metric stack test.
U.S. Department of the Navy **FE0005652**	Understanding of Solid Oxide Fuel Cell Stack in Pressurized Conditions	5	This project focuses on the performance of anode-supported planar SOFCs operating under pressurized conditions in an air-independent environment, consistent with the unmanned undersea vehicle (UUV) application. Pressurized operation is significant benefit for the UUV application, improving system efficiency and reducing system size. More broadly, data from pressurized SOFC operation will, beyond validating performance benefits, give insights into possible R&D necessary for eventual pressurized SOFC deployment in large, stationary power applications. This 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.

CARBON CAPTURE

Although commercially available solvent-based CO_2 capture technologies are being used in various industrial applications, their current state of development is such that they are not ready for widespread deployment on coal-based power plants. The net electrical output from a fossil-based power plant employing currently available 1st-Generation CO_2 capture and compression technologies will be significantly less than that for the same plant without capture. For the plant with capture, a portion of the energy—thermal and electrical—produced at the plant must be used to operate the CO_2 capture and compression processes. Steam usage decreases the gross electrical generation, while the additional auxiliary power usage decreases the net electrical output of the plant. Implementation of 1st-Generation CO_2 capture would generally result in a 7–10 percentage point decrease in net plant efficiency.

FE is investigating a broad portfolio of CO_2-capture research pathways in two general Technology Areas—**PRE-COMBUSTION CAPTURE** and **POST-COMBUSTION CAPTURE**. Pre-combustion capture is mainly applicable to IGCC power plants and refers to removal of CO_2 from syngas prior to its combustion for power production. Post-combustion systems are designed to separate CO_2 from the flue gas produced by fossil fuel combustion in air. These Technology Areas are focused on creating technological advances providing step-change improvements in both cost and performance as compared to current state-of-the-art solvent-based capture systems. Although efforts are focused on capturing CO_2 from the flue gas or syngas of coal-based power plants, the same capture technologies are also applicable to natural-gas- and oil-fired power plants as well as other industrial CO_2 sources.

CARBON CAPTURE

PRE-COMBUSTION CAPTURE

Pre-combustion capture is applicable to IGCC plants, where syngas (a mixture of H_2 and carbon monoxide) is produced by partially combusting coal under pressure in the presence of steam and a limited amount of O_2. After further processing, the carbon monoxide in the syngas is converted into CO_2 and then separated from the H_2. The H_2 is then used as a fuel in a combustion turbine to generate electricity. The Pre-Combustion Capture Technology Area research effort is developing a portfolio of technologies to decrease costs and improve the performance of IGCC plants that capture CO_2.

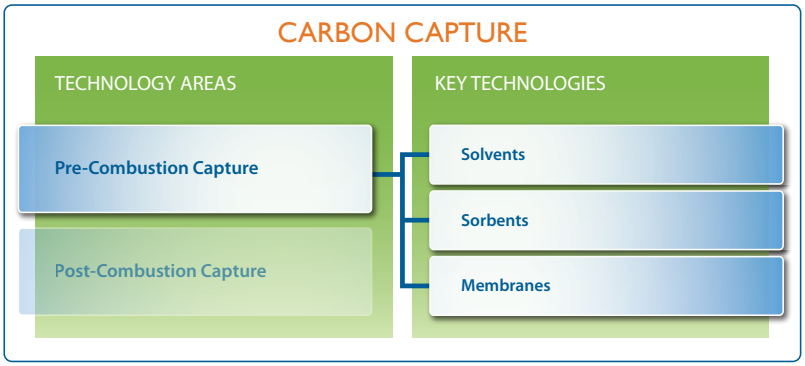


Figure 16. Pre-Combustion Capture Key Technologies

Targets

The Pre-Combustion Capture Technology Area supports the achievement of GPRA Endpoint Performance Target 2—*Advanced Energy Systems with CO_2 capture at no more than $40 per tonne of CO_2 captured by 2020.*

Benefits

Pre-combustion carbon capture technologies focus on the high-temperature/high-pressure removal of CO_2, offering deep emissions reductions for advanced gasification power generation. Alternatively, these technologies can also focus on the concentration of H_2 from a dilute syngas stream, which has applications in liquid fuel and chemical applications and broadens the potential application of pre-combustion capture technology beyond low-carbon power generation. Cost-effective pre-combustion capture technologies will enhance the ability of the United States to use low-cost domestic coal supplies in carbon-constrained fuels and power markets.

Critical Challenges

- CO_2 pressure losses during recovery.
- Multiple heating, cooling, and rehumidification steps reduce efficiency.
- Low solubilities can require circulating large volumes of solvent, resulting in large pump loads.
- Membrane separation of H_2 and CO_2 is challenged by contamination, competitive adsorption, and competitive permeation.
- H_2 and CO_2 recovery often conflicts with purity.
- Materials optimization for harsh conditions.

Projects Assessed

The TRLs of 11 projects were assessed in the Pre-Combustion Capture Technology Area: 3 in Solvents, 1 in Sorbents, and 7 in Membranes. This collective body of work is being pursued to expand the state of knowledge and strengthen the technical basis for the ongoing and planned research in this area.

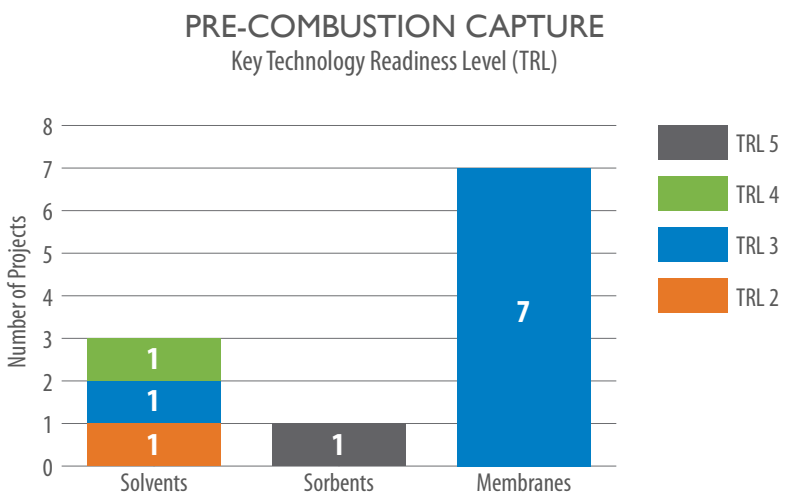


Figure 17. TRL Scores for Pre-Combustion Capture Projects

Rating Summary

The critical technology challenges related to Pre-Combustion Capture require a portfolio of technologies encompassing the three key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the Pre-Combustion Capture technology emerges as a range of TRL values. The overall readiness of the Pre-Combustion Capture Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 2 to 5.

Technology Readiness Level Range for Pre-Combustion Capture

2–5

PRE-COMBUSTION CAPTURE

KEY TECHNOLOGIES

SOLVENTS

Pre-combustion solvent-based CO_2 capture involves chemical or physical absorption of CO_2 from flue gas into a liquid absorbent. As the name implies, a chemical solvent relies on a chemical reaction for absorption, whereas a physical solvent selectively absorbs CO_2 without a chemical reaction. The main benefit of a physical solvent, as compared to a chemical solvent, is that it requires less energy for regeneration. However, chemical solvents offer the advantages of increased mass transfer driving force into solution, increased acid gas selectivity, and the potential to generate the CO_2 at elevated pressure. Challenges associated with solvent-based pre-combustion CO_2 capture include modifying regeneration conditions to recover the CO_2 at a higher pressure, improving selectivity to reduce H_2 losses, and developing a solvent that has high CO_2 loading at a higher temperature to improve IGCC efficiency.

3
PROJECTS
2–4
TRL RANGE

Three projects within the Carbon Capture Pre-Combustion Capture portfolio focused on improving solvent-based technologies were assessed. The current TRLs of this key technology range from 2–4 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

SORBENTS

1 PROJECT
5 TRL RANGE

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. A temperature or pressure swing facilitates sorbent regeneration following chemical and/or physical adsorption. Possible configurations for contacting the syngas with the sorbents include fixed, moving, and fluidized beds. Research projects in sorbent technology focus on the development of sorbents with the following characteristics: high adsorption capacity, resistance to attrition over multiple regeneration cycles, and good CO_2 separation and selectivity performance at the high temperatures encountered in IGCC systems to avoid the need for syngas cooling. Another important focus of the research is to develop cost-effective process equipment designs that are tailored to the sorbent characteristics.

One project within the Carbon Capture Pre-Combustion Capture portfolio focused on improving sorbent-based technologies was assessed. The current TRL of this project is 5 for the ongoing work, consistent with the status of the individual technologies embedded within this project.

MEMBRANES

7 PROJECTS
3 TRL RANGE

Pre-combustion membrane-based CO_2 capture uses permeable materials that allow for the selective transport and separation of CO_2 or H_2 from the syngas. Different types of membrane materials are available, including polymeric membranes, porous inorganic membranes, palladium membranes, and zeolite membranes. Membrane separation uses partial-pressure difference as the driving force and is thus suitable for pre-combustion CO_2 capture because the gas is often available at high pressures. Gas-separation membranes are based on differences in physical or chemical interactions between gases and the membrane material, thereby allowing one component to pass through the membrane at a faster rate than the other components. The separation efficiency is determined by the membrane selectivity. Usually the selectivity of the membranes in one stage is insufficient to achieve the desired purities and recoveries, so multiple stages and recycling may be required in an actual operation, leading to increased complexity, energy consumption, and capital costs. Methods must be found to improve separation and throughput and prevent membranes from becoming less effective over time. The main properties of a membrane that could improve performance are CO_2 selectivity and permeability. While critical research is focused in these areas, the thermal and hydrothermal stabilities of the membrane, as well as other physical and chemical properties, also need to be considered. Scaleup studies must determine the potential for lower cost and efficient operation in integrated systems. Large-scale manufacturing methods for defect-free membranes and modules must be developed. Better methods are needed to make high-temperature, high-pressure seals using ceramic substrates. To address these technology challenges, FE is funding the development of a wide variety of membrane-based systems for pre-combustion CO_2 capture.

Seven projects within the Carbon Capture Pre-Combustion Capture portfolio focused on improving membrane-based technologies were assessed. The current TRL of this project is 3 for the ongoing work, consistent with the status of the individual technologies embedded within this project.

PRE-COMBUSTION CAPTURE
PORTFOLIO

Table 10. **Pre-Combustion Capture Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Solvents			
NETL-ORD **FWP-2012.01.02**	ORD Capture FWP—Task 2: Pre-Combustion Solvents	3	This project focuses on development and optimization of polydimethylsiloxane (PDMS) solvents. PDMS solvents have favorable hydrophobicity, CO_2 capacity, kinetics, and viscosity; near-zero vapor pressure; and may be stable at elevated temperatures, all leading to reduced operating costs. Specifically, this project involves modeling and bench-scale testing of PDMS solvent formulations using both simulated and actual syngas.

Table 10. **Pre-Combustion Capture Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
NETL-ORD **FWP-2012.01.09**	ORD Capture FWP—Task 9: Pre-Combustion Transformational Technologies	2	The focus of this project is to examine breakthrough concepts in pre-combustion solvents, sorbents, and membranes. Because of the revolutionary nature of these technologies, a single success will significantly lower costs and energy requirements. Specifically, this work will focus on development of structured liquid capture media-metallic complexes and eutectic mixtures designed for low viscosity.
SRI International **FE0000896**	CO_2 Capture from IGCC Gas Streams Using the AC-ABC Process	4	This project focuses on developing a high-capacity aqueous ammoniated capture solvent containing ammonium carbonate (AC), which reacts with CO_2 to form ammonium bicarbonate (ABC). The system utilizes a single absorber to co-capture CO_2 and H_2S from syngas, followed by a Bechtel Claus unit to separate the sulfur from the CO_2, increasing efficiency and reducing operating costs. Specifically, this project involves bench-scale testing of the AC-ABC system.
Key Technology—Sorbents			
TDA Research, Inc. **FE0013105**	Pilot Testing of a Highly Effective Pre-Combustion Sorbent-Based Carbon Capture System	5	This project focuses on scaling up a novel carbon sorbent-based pre-combustion capture technology. CO_2 is captured above the dew point and at pressure that significantly improves net plant efficiency and decreases operating costs. Specifically, 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.
Key Technology—Membranes			
Arizona State University **FE0000470**	Pre-Combustion Carbon Dioxide Capture by a New Dual-Phase Ceramic Carbonate Membrane Reactor	3	This project focuses on the development of a high-temperature, chemically stable, and CO_2 perm-selective dual-phase membrane. For this system, the water-gas-shift reaction and the separation of CO_2 and H_2 are completed at one temperature, which increases efficiency, decreasing operating costs. Specifically, in this project a dual-phase ceramic-carbonate membrane will be synthesized and tested at laboratory scale.
Los Alamos National Laboratory **FWP-308-13**	Polymer-Based Carbon Dioxide Capture Membrane Systems	3	This project focuses on the research and development of a polybenzimidazole (PBI) membrane capture technology. The CO_2 is separated at a higher pressure, and the membranes are tolerant of impurities reducing both capital and operating costs. Specifically, asymmetric PBI hollow fibers composed of a thin dense selective layer and an open, porous underlying support structure with optimized transport and property requirements will be produced and tested at bench scale with simulated syngas.
Media and Process Technology, Inc. **FE0013064**	Robust and Energy Efficient Dual-Stage Membrane-Based Process for Enhanced Carbon Dioxide Recovery	3	This project focuses on developing a dual-stage membrane process that couples a hydrogen-selective carbon molecular sieve membrane in a water-gas-shift membrane reactor with a Pd-based membrane for residual hydrogen recovery. The dual-stage membrane process achieves high-hydrogen recovery and CO_2 capture efficiency with minimal or no parasitic energy consumption, thereby decreasing operating costs. Specifically, this project involves bench-scale testing with real syngas.
NETL-ORD **FWP-2012.01.04**	ORD Capture FWP—Task 4: Pre-Combustion Membranes	3	This project focuses on the development of supported ionic liquid membranes (SILMs). SILMs make use of a glassy polymer that supports an ionic liquid to integrate ionic liquids into a polymer membrane, increasing the selectivity and permeance of the membrane, and lowering operating costs. Specifically, SILMs will be tested at high temperature and high pressure to simulate pre-combustion capture conditions at the bench scale.
Pall Corporation **FE0001181**	Designing and Validating Ternary Pd Alloys for Optimum Sulfur/Carbon Resistance	3	This project focuses on developing an efficient, economically viable, high-temperature/pressure, Pd-based H_2/CO_2 separation membrane system. The membrane consists of an ultrathin Pd-alloy deposited on porous, ceramic-coated stainless steel tubes with high H_2 flux and selectivity, decreasing operating costs. Specifically, this project will test Pd-alloy disks in a simulated syngas environment.
SRI International **FE0012965**	Development of a Pre-Combustion Carbon Dioxide Capture Process Using High-Temperature Polybenzimidazole Hollow-Fiber Membrane	3	This project focuses on the evaluation of a PBI membrane-based process for separation of H_2 and CO_2. The membrane consists of hollow-fiber PBI, which is intrinsically chemically and thermally stable at temperatures up to 450 °C (but due to temperature constraints of associated materials will be operated in the 200–250 °C range) and pressures up to 55 atm, negating the need for cooling after water gas shift, increasing efficiency, and reducing operating costs. Specifically, asymmetric hollow-fiber membranes will be fabricated and tested at 50-kWth scale using actual syngas.
University of Minnesota **FE0001322**	Hydrogen Selective Exfoliated Zeolite Membranes	3	This project focuses on development of a novel silica molecular sieve capture membrane. The membrane technology forms a selective film using a coating process and premade components, and will have high selectivity, flux, and stability to decrease capital and operating costs. Specifically, this project will establish procedures for the production of layered silicates and test the resulting membrane at laboratory scale using simulated syngas.

CARBON CAPTURE

POST-COMBUSTION CAPTURE

The Post-Combustion Capture Technology Area research effort is developing a portfolio of post-combustion CO_2 capture technologies to decrease costs and improve the performance of PC power plants that capture CO_2 produced as part of the combustion process.

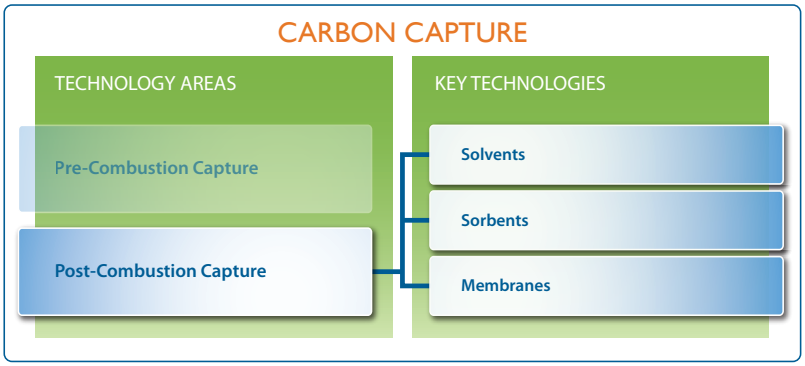


Figure 18. Post-Combustion Capture Key Technologies

Targets

The Post-Combustion Capture Technology Area supports the achievement of GPRA Endpoint Performance Target 2—*Advanced Energy Systems with CO_2 capture at no more than $40 per tonne of CO_2 captured by 2020.*

Benefits

FE estimates that the deployment of current state-of-the-art post-combustion CO_2 capture technology on a new PC power plant would increase COE by approximately 80 percent and derate the plant's net generating capacity by as much as 30 percent due to the steam and auxiliary power required to operate the capture system. Efficient and cost-effective post-combustion capture technologies are therefore critical to ensuring the long-term viability of coal-fired power generation. It is widely recognized that development of cost-effective post-combustion capture technologies must be an essential component of efforts to reduce future emissions of CO_2.

Critical Challenges

- Improving the performance and cost of capture materials (solvents, sorbents, and membranes).
- Decreasing parasitic loads.
- Effective integration with other power plant processes.
- Scale-up to industrial scale.
- Reducing the impacts of other flue gas contaminants on the CO_2 capture process.

Projects Assessed

The TRLs of 47 projects were assessed in the Post-Combustion Capture Technology Area: 21 in solvents, 16 in sorbents, and 10 in membranes. This collective body of work is being pursued to expand the state of knowledge and strengthen the technical basis for the ongoing and planned research in this area.

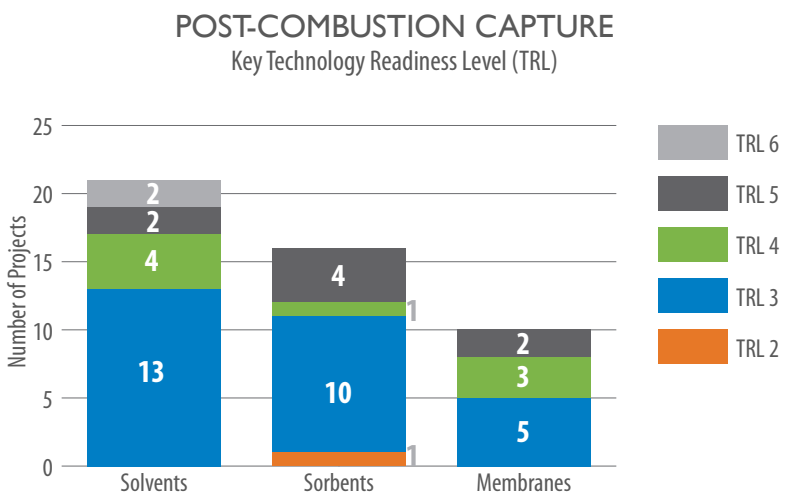


Figure 19. TRL Scores for Post-Combustion Capture Projects

Rating Summary

The critical technology challenges related to Post-Combustion Capture require a portfolio of technologies encompassing the three key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the Post-Combustion Capture technology emerges as a range of TRL values. The overall readiness of the Post-Combustion Capture Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 2 to 6.

Technology Readiness Level Range for Post-Combustion Capture

2–6

POST-COMBUSTION CAPTURE

KEY TECHNOLOGIES

SOLVENTS

21 PROJECTS
3–6 TRL RANGE

Post-combustion solvent-based CO_2 capture involves chemical or physical absorption of CO_2 from flue gas into a liquid absorbent. Solvent-based systems are in commercial use today scrubbing CO_2 from industrial flue gases and process gases; however, they have not been applied to removing large volumes of CO_2, as would be encountered in the flue gas from coal-fired power plants, nor have they demonstrated efficient, full integration into the balance-of-plant. Research projects in this pathway address technical challenges to solvent-based CO_2 capture, such as large flue gas volume, relatively low CO_2 concentration, flue gas contaminants, high parasitic power demand for solvent regeneration, and increased water consumption. FE's RD&D focus for post-combustion solvents includes development of low-cost noncorrosive solvents that have a high-CO_2 loading capacity, improved reaction kinetics, low regeneration energy, and resistance to degradation.

Twenty-one projects within the Carbon Capture Post-Combustion Capture portfolio focused on improving solvent-based technologies were assessed. The current TRLs of this key technology range from 3–6 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

SORBENTS

16 PROJECTS
2–5 TRL RANGE

Solid sorbents—including sodium and potassium oxides, zeolites, carbonates, amine-enriched sorbents, and MOFs—are also being explored for post-combustion CO_2 capture. A temperature swing facilitates sorbent regeneration following chemical and/or physical adsorption, but a key attribute of CO_2 sorbents is that water is not present as a carrier, compared to solvent-based systems, thereby reducing the sensible heating and stripping energy requirements. Possible configurations for contacting the flue gas with the sorbents include fixed, moving, and fluidized beds. Research projects in this pathway focus on the development of sorbents with the following characteristics: low-cost raw materials, thermally and chemically stable materials, low attrition rates, low heat capacity, high CO_2 absorption capacity, and high CO_2 selectivity. Another important focus of the research is to develop cost-effective process and equipment designs that are tailored to the sorbent characteristics.

Sixteen projects within the Carbon Capture Post-Combustion Capture portfolio focused on improving sorbent-based technologies were assessed. The current TRLs of this key technology range from 2–5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

MEMBRANES

10 PROJECTS
3–5 TRL RANGE

Post-combustion membrane-based CO_2 capture uses permeable or semi-permeable materials that allow for the selective transport and separation of CO_2 from flue gas. Generally, gas separation is accomplished by some physical or chemical interaction between the membrane and the gas being separated, causing one component in the gas to permeate through the membrane faster than another. Usually the selectivity of the membrane is insufficient to achieve the desired purities and recoveries; therefore multiple stages and recycle streams may be required in an actual operation, leading to increased complexity, energy consumption, and capital costs. Research has been conducted with a number of different types of gas separation membranes, including polymer, facilitated transport, and molecular sieves. Gas absorption membrane technologies are also under development, where the separation is caused by the presence of an absorption liquid on one side of the membrane that selectively removes CO_2 from a gas stream on the other side of the membrane. Research projects in this pathway address key technical challenges to the use of membrane-based systems, such as large flue gas volume, relatively low CO_2 concentration, low flue gas pressure, flue gas contaminants, and the need for high membrane surface area. FE's RD&D focus for post-combustion membranes includes development of low-cost, durable membranes that have improved selectivity, thermal and physical stability, tolerance to contaminants in combustion flue gas, and process improvements including hybrid and fully integrated system configurations.

Ten projects within the Carbon Capture Post-Combustion Capture portfolio focused on improving membrane-based technologies were assessed. The current TRLs of this key technology range from 3–5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

POST-COMBUSTION CAPTURE

PORTFOLIO

Table 11. **Post-Combustion Capture Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Solvents			
Akermin, Inc. **FE0012862**	Novel Flow Sheet for Low-Energy CO_2 Capture Enabled by Biocatalyst Delivery System	3	This project focuses on development of an enzyme-catalyzed solvent capture process using a next-generation biocatalyst delivery system (BDS) and a nonvolatile solvent blend. Optimization of the BDS performance will enable on-stream biocatalyst replacement, increasing efficiency and reducing operating cost, while enhanced kinetics of the advanced solvent will reduce reactor size and thus capital cost. Specifically, the process and solvent will be tested using an existing bench-scale unit.
Babcock & Wilcox Power Generation Group, Inc. **FE0007716**	Development of an Energy Efficient, Environmentally Friendly Solvent for the Capture of CO_2	3	This project focuses on optimizing a novel piperazine (PZ)-blend solvent formulation for cost-effective, energy-efficient CO_2 capture. Concentrated PZ has demonstrated high absorption rates and low regeneration energy, but recent testing indicates that PZ-blends with other organic compounds perform substantially better than PZ alone, decreasing both capital and operating costs. Specifically, this project will identify optimal PZ blends through bench-scale thermodynamic and kinetic analyses.
Battelle Memorial Institute **FE0007466**	CO_2 Binding Organic Liquids Gas Capture with Polarity-Swing-Assisted Regeneration	3	This project focuses on optimizing the formulation of a CO_2 binding organic liquid (CO_2BOL) solvent combined with a novel polarity-swing-assisted-regeneration (PSAR) process. The process relies on significantly reduced regeneration temperatures, lowering regeneration energy, parasitic load, solvent losses, thermal degradation, and thus operating costs. Specifically, this project will involve bench-scale testing to measure CO_2 loading and verify performance of coupling CO_2BOLs with PSAR.
Carbon Capture Scientific, LLC **FE0007567**	Development of a Novel Gas Pressureized Stripping Process-Based Technology for CO_2 Capture	3	This project focuses on reducing the parasitic power requirement for CO_2 capture through development and demonstration of a novel gas pressurized stripping (GPS) technology applicable to solvent-based processes. GPS operates at higher solvent regeneration pressures than conventional technologies, which reduces the CO_2 compression requirements (and thus capital and operating costs) for delivery to pipelines. Specifically, this project will demonstrate and evaluate a GPS system at bench scale.
GE Global Research **FE0013687**	Bench-Scale Process for Low-Cost CO_2 Capture Using a Phase-Changing Absorbent	3	This project focuses on developing and testing an amino-silicone-based phase-change process for CO_2 capture. The solvent readily forms a solid in the presence of CO_2 in a thermally reversible reaction with no degradation of the solvent, which decreases operating cost. Specifically, bench-scale testing and analysis will be conducted to show the feasibility and scalability of the process.
General Electric Company **FE0007502**	Bench-Scale Silicone Process for Low-Cost CO_2 Capture	4	This project is developing an amino-silicone CO_2 capture solvent. The solvent's high thermal stability, high working capacity, and low volatility reduce capture system parasitic power requirements, reducing operating costs. Specifically, this project will test the solvent in a continuous bench-scale system and develop a rigorous process model and manufacturability analysis that will enable development at larger scales.
General Electric Company **FE0013755**	Pilot-Scale Silicone Process for Low-Cost Carbon Dioxide Capture	4	This project focuses on establishing scalability and the techno-economic feasibility of using an amino-silicone-based solvent for post-combustion capture. The high thermal stability, high working capacity, and low volatility of the solvent reduce capture system parasitic power requirements and reduce operating costs. Specifically, this project will design and operate a 0.5-MWe slipstream-scale process at NCCC.
ION Engineering, LLC **FE0013303**	Ion Advanced Solvent CO_2 Capture Pilot Project	5	This project focuses on the development and scaleup of a capture process using a nonaqueous solvent/amine mixture. Physical and chemical solvent properties can be manipulated, which impact reaction rates and thermal requirements, thereby reducing capital and operating costs. Specifically, the process will be demonstrated at the 0.8-MWe scale at an operating coal-fired power plant.
Lawrence Berkeley National Laboratory **FWP-MSKCBS**	Taking Fundamentally New Materials for CO_2 Capture Toward Applications: A Synergistic Effort	3	This project is focused on developing a coherent research effort linking a molecular understanding of materials to their performance in a carbon-capture process. The research will help to identify potential bottlenecks associated with novel materials currently under development at a very early stage of research when these can be more easily mitigated, allowing for successful implementation of these low-capital and -operating cost, low-energy technologies. Specifically, MOFs will be characterized and fabricated.

Table 11. **Post-Combustion Capture Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Linde, LLC **FE0007453**	Slipstream Pilot-Scale Demonstration of a Novel Amine-Based Post-Combustion Process Technology for CO_2 Capture from Coal-Fired Power Plant Flue Gas	6	This project focuses on refining a capture technology incorporating BASF's novel amine-based solvent. The solvent provides significant reduction in regeneration steam consumption, electrical power, and cooling water, and is readily scalable to large capacities with a single-train system, further reducing capital and operating costs. Specifically, this project will design and build a 1-MWe pilot plant and conduct long-term testing to demonstrate solvent stability.
NETL-ORD **FWP-2012.01.05**	ORD Capture FWP—Task 5: Post-Combustion Solvents	3	This project focuses on the examination of aprotic heterocyclic anion ionic liquids and amino acid solutions as capture solvents. These solvents offer the potential for higher working capacities and lower regeneration energies, resulting in lower capital costs and energy penalties than conventional solvents. Specifically, the effects of capacity, sensible heat, and heat of vaporization on the capture system performance will be evaluated.
Neumann Systems Group, Inc. **FE0007528**	Carbon Absorber Retrofit Equipment (CARE)	5	This project focuses on pilot-scale testing of a unique, nozzle-based solvent contacting system. The solvent jets generated by the nozzles increase solvent/flue gas contacting and significantly reduce capture system footprint/capital cost, cost of capture, and COE. Specifically, this project will involve parametric and long-term testing of the nozzle-based system at 0.5-MWe scale using a flue gas slipstream from an operating coal-fired power plant.
Novozymes North America, Inc. **FE0007741**	Low-Energy Solvents for CO_2 Capture Enabled by a Combination of Enzymes and Ultrasonics	3	This project focuses on reducing costs and parasitic power requirements for CO_2 capture using a low-energy potassium carbonate-based solvent in combination with an enzyme catalyst (carbonic anhydrase). The enzyme speeds absorption reactions allowing for reduced absorber size and lower capital costs, while the solvent decreases regeneration energy and operating costs. Specifically, this project will design, build, and test an integrated bench-scale system optimized for the specific solvent/catalyst.
Research Triangle Institute **FE0013865**	Bench-Scale Development of a Nonaqueous Solvent CO_2 Capture Process for Coal-Fired Power Plants	3	This project focuses on the development of a nonaqueous solvent (NAS)-based CO_2 capture process. NAS increases efficiency by reducing parasitic power load for sorbent regeneration, reducing operating costs. Specifically, bench-scale testing will be used to demonstrate the potential to reduce thermal regeneration energy.
Southern Company Services, Inc. **FE0007525**	Development and Demonstration of Waste Heat Integration with Solvent Process for More Efficient CO_2 Removal	6	This project is focused on improving energy performance by integrating a flue gas high-efficiency system (HES) waste heat recovery technology into a pilot amine-based CO_2 capture process and host PC unit. Recovered heat from the HES and that from the CO_2 product gas cooler is used to preheat boiler feed-water, resulting in improved overall power plant performance and reduced capital and operating costs. The HES technology also has the potential for enhanced removal of sulfur trioxide and trace metals from the flue gas as a result of improved electrostatic precipitator performance. This improvement has the added benefits of reducing amine solvent loss and accumulation of metals, thereby reducing operating costs of the solvent capture process. Specifically, this project will demonstrate HES system integration with a 25-MW KM CDR® pilot process and Southern Company's Plant Barry.
SRI International **FE0012959**	Development of Mixed-Salt Technology for Carbon Dioxide Capture from Coal Power Plants	3	This project focuses on testing a low-cost, ammonia-based, mixed-salt, solvent capture technology. The mixed-salt technology combines existing ammonium and potassium carbonate technologies with improved absorption steps for rate enhancement and a novel selective regeneration process to reduce capital and operating costs. Specifically, this project will demonstrate the absorber and regenerator processes individually through bench-scale testing.
University of Illinois **FE0004360**	Bench-Scale Development for a Hot Carbonate Absorption Process with Crystallization-Enabled High-Pressure Stripping for Post-Combustion Capture	3	This project focuses on reducing capital and operating costs and energy requirements for CO_2 capture using the hot carbonate absorption process with crystallization-enabled high-pressure stripping. The crystallization process allows for high-pressure stripping, reducing compression costs, and high absorption temperature improves absorption kinetics. Specifically, this project will determine process feasibility by conducting bench-scale analyses of thermodynamic and kinetic data.
University of Kentucky **FE0007395**	Application of a Heat-Integrated Post-Combustion CO_2 Capture System with Hitachi Advanced Solvent into Existing Coal-Fired Power Plant	4	This project will contribute to program goals by developing a process using a two-stage stripping concept that reduces both capital and operating costs. The two-stage stripping unit will regenerate a CO_2-lean solvent, increasing the rate of CO_2 absorption, while the primary CO_2 stripper can be operated at high pressure in order to maximize the energy benefit. Specifically, this project will implement the two-stage stripping process concept in a 0.7-MW slipstream pilot-scale system.
University of Kentucky **FE0012926**	An Advanced Catalytic Solvent for Lower Cost Post-Combustion CO_2 Capture in a Coal-Fired Power Plant	3	This project focuses on testing two technologies to improve solvent-based capture—absorption catalyzation and membrane dewatering of CO_2-loaded solvent. Small-molecule organometallic carbonic anhydrase enzyme mimics enhance absorber kinetics, and dewatering increases stripper driving force, yielding reductions in capital and operating costs. Specifically, impacts of these technologies will be evaluated through bench-scale parametric testing.

Table 11. **Post-Combustion Capture Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
URS Group, Inc. **FE0005654**	Evaluation of Concentrated Piperazine for CO_2 Capture from Coal-Fired Flue Gas	4	This project focuses on mitigating capture cost and performance impacts using a concentrated PZ solvent. Concentrated PZ offers higher working capacity, thermal stability, and stripper pressure, faster CO_2 absorption, and less oxidative degradation to decrease compressor requirements as well as capital and operating costs. Specifically, this project will involve bench-scale process testing followed by scaleup to the 0.5-MW scale.
William Marsh Rice University **FE0007531**	Combined Pressure, Temperature Contrast, and Surface-Enhanced Separation of CO_2 for Post-Combustion Carbon Capture	3	This project is developing a hybrid CO_2 absorption process combining absorber and stripper columns into a single unit and using a high-surface-area ceramic foam gas-liquid contactor. Low-temperature regeneration using waste heat will reduce parasitic load, amine losses and equipment corrosion, reducing operating cost, and use of a single unit reduces capital cost. Specifically, this project will develop and test the stripper unit, functionalize and optimize the properties of the ceramic foam, and develop a model for the CO_2 absorption process.
Key Technology—Sorbents			
ADA-ES, Inc. **FE0004343**	Evaluation of Solid Sorbents as a Retrofit Technology for CO_2 Capture	5	This project is focused on the scaleup of an advanced amine-based sorbent capture technology. The sorbent has high working capacity and low heat capacity leading to decreased capital costs and energy requirements. Specifically, this project will undertake design, engineering, fabrication, construction, and operation of 1-MW pilot at Southern Company's Plant Miller.
ADA-ES, Inc. **FE0012914**	Optimizing the Costs of Solid Sorbent-Based CO_2 Capture Process Through Heat Integration	3	This project focuses on evaluating heat integration opportunities for dry sorbent-based post-combustion systems. The enabling technology being developed has the potential for wide application to sorbent-based processes and can lead to decreased operating costs. Specifically, heat recovery for temperature swing adsorption, including the use of cross heat exchange to recover sensible heat from the sorbent leaving the regenerator, will be investigated.
Alliant Techsystems Operations, LLC **FE0013122**	Supersonic Post-Combustion Inertial CO_2 Extraction System	3	This project focuses on utilizing a unique aero-thermodynamic inertial separation device derived from aerospace applications to capture CO_2. The inertial CO_2 extraction system converts vapor-phase CO_2 to solid via supersonic expansion followed by inertial separation, resulting in decreased capital and operating costs. Specifically, bench-scale testing will be conducted to confirm the feasibility of the process.
Aspen Aerogels, Inc. **FE0013127**	Bench-Scale Development and Testing of Aerogel Sorbents for CO_2 Capture	3	This project focuses on scaleup and testing of an advanced aerogel sorbent-based capture technology. The aerogels have high surface area and porosity and excellent hydrophobicity for resisting performance degradation from moisture and flue gas contaminants, resulting in reduced operating costs. Specifically, the performance of amine-functionalized powdered and pelletized aerogel formulations will be assessed at the bench scale.
Georgia Tech Research Corporation **FE0007804**	Rapid Temperature Swing Adsorption Using Polymer/Supported Amine Composite Hollow Fibers	3	This project focuses on development of a rapid temperature swing adsorption (RTSA) process using polymeric hollow-fiber contactors loaded with amine-based sorbents, surrounding an impermeable heating/cooling layer. Temperature control during both adsorption and regeneration maximizes working capacity and reduces cycle times and device volume, reducing capital expenditures. Specifically, flexible hollow fibers will be manufactured and tested in a bench-scale RTSA unit.
Innosepra, LLC **FE0007948**	Bench-Scale Development and Testing of a Novel Adsorption Process	3	The focus of this project is the development of a sorption-based capture technology using a combination of novel microporous materials and process cycles. This unique combination allows for use of physical sorbents to generate the same purity and recovery as chemical sorbents and amine-based absorption with lower operating costs. Specifically, process data, adsorption/desorption isotherms and heat and mass transfer rate measurements will be made followed by bench-scale component testing using actual flue gas.
NETL-ORD **FWP-2012.01.06**	ORD Capture FWP—Task 6: Post-Combustion Sorbents	3	This project focuses on the development of amine-enriched sorbents and associated process and reactor design development. These sorbents exhibit increased working capacity, chemical stability, and mechanical durability versus currently available sorbent materials, resulting in lower capital and operating costs and higher efficiencies. Specifically, kinetic studies, thermodynamic property evaluation, and solids transport characteristics of the sorbent material will be evaluated.
NETL-ORD **FWP-2012.01.10**	ORD Capture FWP—Task 10: Post-Combustion Transformational Technologies	2	The focus of this project is to examine breakthrough concepts in solvents, sorbents, and membranes. Because of the revolutionary nature of these technologies, a single success will significantly lower capital and operating costs and energy requirements. Specifically, this work will focus on advanced systems integration approaches in addition to the development of advanced materials.

Table 11. **Post-Combustion Capture Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Ramgen Power Systems **FE0000493**	Ramgen Supersonic Shock Wave Compression and Engine Technology	4	This project focuses on development of a supersonic shock wave CO_2 compression technology. The technology reduces capital cost and the COE via its ability to achieve a targeted pressure ratio with fewer compression stages and a smaller overall compressor size, while maintaining a competitive operating efficiency. Specifically, this project will design, construct, and test a prototype supersonic shock wave CO_2 compressor with a targeted pressure ratio of 10:1 and a suction pressure of 210 psia.
Research Triangle Institute **FE0007707**	Novel Solid Sorbents for Post-Combustion CO_2 Capture	3	This project focuses on the development of polymeric amine-based solid sorbents for CO_2 capture. The reactor design offers superior gas-solid heat and mass transfer, providing potential for reduced parasitic loads and lower capital and operating costs than conventional technology. Specifically, this project seeks to improve the thermal and chemical stability of the base polymer, transition the current fixed-bed sorbent into a fluidizable form, and prove the efficiency of the reactor design.
Southwest Research Institute **FC26-05NT42650**	Novel Concepts for the Compression of Large Volumes of Carbon Dioxide	5	This project focuses on the investigation of various methods to pressurize CO_2 to pipeline pressure with decreased parasitic power consumption and cost, including validation testing of select technologies. Reduced compression power requirements and lower equipment costs result in increased plant efficiency, and reduced COE. This project will develop and construct a pilot-scale compression test loop to validate the technology.
SRI International **FE0013123**	Pilot-Scale Evaluation of an Advanced Carbon Sorbent-Based Process for Post-Combustion Carbon Capture	5	This project focuses on testing an innovative, low-cost, low-energy, CO_2 capture technology based on adsorption with a high-capacity, attrition-resistant carbon sorbent. The adsorption process has low activation energy and rapid cycling, which reduces capital and operating costs. Specifically, a 1-MWe slipstream pilot plant will be designed, built, and operated at NCCC.
SRI International **NT0005578**	Development of Novel Carbon Sorbents for CO_2 Capture	5	The focus of this project is the development of a low-cost, low-energy, high-capacity carbon-based sorbent. The low-heat capacity of the sorbent minimizes the thermal energy needed to heat the sorbent to the regeneration temperature, lowering operating costs and energy penalty. Specifically, sorbent properties such as surface area, heat of adsorption and desorption, compressive strength, and attrition resistance will be evaluated along with performance in the presence of coal-fired flue gas.
TDA Research, Inc. **FE0007580**	A Low-Cost, High-Capacity Regenerable Sorbent for CO_2 Capture from Existing Coal-Fired Power Plants	3	The focus of this project is the development of a low-cost, high capacity carbon-based CO_2 capture sorbent. The material is highly selective, has low heat of adsorption, low net regeneration energy, and is contaminant-resistant, all contributing to low capital and operating costs. Specifically, this project will optimize the physical properties and mechanical integrity of the sorbent and identify optimum operating conditions and process parameters for design calculations.
University of North Dakota **FE0007603**	Evaluation of CO_2 Capture from Existing Coal-Fired Plants by Hybrid Sorption Using Solid Sorbents (CACHYS™)	3	The focus of this project is the development of a solid sorbent capture process. The technology employs novel chemistry, low-cost heat management, and heat of adsorption minimization to drive down capital and energy costs. Specifically, the project involves bench-scale process testing along with determination of sorbent capacity with continuous cycling, kinetics and sorption energetics, attrition resistance, and optimal operating conditions.
W. R. Grace & Co. **FE0007639**	Bench-Scale Development and Testing of Rapid PSA for CO_2 Capture	3	This project focuses on developing a rapid PSA process. The process incorporates a structured adsorbent with low-pressure drop, high mass-transfer rates, high capacity, and high availability that will enable large feed throughputs, reducing operating costs. Specifically, this project will develop a bench-scale rapid PSA cycle configuration using the structured adsorbent resulting in improved performance at reduced capital and operating costs.
Key Technology—Membranes			
American Air Liquide, Inc. **FE0013163**	CO_2 Capture by Cold Membrane Operation with Actual Power Plant Flue Gas	4	This project focuses on the development of a novel CO_2 capture process with cold-temperature membrane operation. The membrane will be coupled with cryogenic processing technology that will decrease operating costs. Specifically, this project will down-select from two alternative membrane materials and optimize hollow-fiber membrane bundles in a closed-loop test system to demonstrate performance and verify the effect of possible contaminants using simulated and actual flue gas.
FuelCell Energy, Inc. **FE0007634**	Electrochemical Membranes for Carbon Dioxide Capture and Power Generation	3	This project focuses on developing an electrochemical membrane (ECM)-based system for CO_2 capture that also provides additional electrical power generation. The ECM technology will reduce NO_x emissions, increase net efficiency, enhance power generation, and reduce capital and operating costs for CO_2 capture. Specifically, this project will design and complete bench-scale testing of a molten carbonate fuel cell/capture system.

Table 11. **Post-Combustion Capture Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Gas Technology Institute **FE0004787**	Hybrid Membrane/Absorption Process for Post-Combustion CO_2 Capture	4	This project focuses on the development of a process that combines solvent absorption and a hollow-fiber membrane to leverage capture cost and performance advantages. The hybrid technology increases interfacial gas/liquid area by a factor of 10, requires lower steam regeneration energy, and CO_2 is generated at pressure, which increases mass transfer and decreases capital and operating cost. Specifically, this project will develop and test a bench-scale hybrid membrane contactor module.
Gas Technology Institute **FE0012829**	Pilot Test of a Nanoporous, Super-Hydrophobic Membrane Contactor Process for Post-Combustion CO_2 Capture	5	The project focus is to scale-up a hybrid technology that employs a polyether ether ketone (PEEK) hollow-fiber membrane contactor and Hitachi's advanced H3-1 solvent. The technology increases effective interfacial gas/liquid area by a factor of 10, which increases mass transfer and decreases capital and operating costs. Specifically, field tests will be conducted on a 1-MWe pilot-scale unit using actual flue gas at NCCC.
General Electric Company **FE0007514**	Bench-Scale High-Performance Thin Film Composite Hollow-Fiber Membranes for Post-Combustion Carbon Dioxide Capture	3	This project focuses on optimizing the performance and manufacturability of a novel phosphazene polymer membrane. The hollow-fiber membrane reduces fly ash adhesion, is highly scalable, and decreases operating cost by increasing membrane life. Specifically, this project focuses on developing processes to apply thin layer coatings on hollow-fiber supports and elucidating fundamental polymer properties for use in composite-coated hollow-fiber membranes.
Membrane Technology and Research, Inc. **FE0005795**	Slipstream Testing of a Membrane CO_2 Capture Process for Existing Coal-Fired Power Plant	5	This project focuses on scaleup of a high-permeance polymer-based membrane and process design. The process includes an air sweep step that transfers recycled CO_2 to the boiler, increasing the driving force in the initial cross-flow membrane stage, reducing the required membrane area, total capital cost, and the overall energy cost. Specifically, this project will design, construct and test a 1-MW capacity membrane skid at NCCC.
Membrane Technology and Research, Inc. **FE0007553**	Low-Pressure Membrane Contactors for CO_2 Capture	4	This project focuses on the development of a compact, large-membrane-area, low-pressure-drop, plate-and-frame sweep module. The sweep module represents an enabling technology to the spiral-wound MTR membrane process by recycling CO_2 to the boiler with an air sweep, increasing CO_2 concentration in the flue gas, and ultimately reducing energy costs. Specifically, prototype laboratory modules will be constructed and demonstrated and then scaled up to a full-scale module that will be tested at NCCC.
Membrane Technology and Research, Inc. **FE0013118**	Bench-Scale Development of a Hybrid Membrane-Absorption CO_2 Capture Process	3	This project focuses on optimizing the configuration of a hybrid CO_2 capture system that combines amine absorption and membrane technology. Polaris™ membranes will be combined with an improved amine solvent-based capture system to increase efficiency and decrease capital and operating costs. Specifically, a bench-scale system will be constructed and two design variations will be tested.
NETL-ORD **FWP-2012.01.07**	ORD Capture FWP—Task 7: Post-Combustion Membranes	3	The focus of this project is to evaluate mixed matrix membranes that contain MOFs. Integrating MOFs into a polymer membrane increases the selectivity and permeance of the membrane, lowering capital costs and energy requirements. Specifically, multiple techniques will be employed to improve polymer/MOF compatibility including creation of strongly MOF-interactive polymers, layer-by-layer polymer encapsulation of MOF nanocrystals, and emulsion-based fabrication techniques.
Ohio State University Research Foundation **FE0007632**	Novel Inorganic/Polymer Composite Membranes	3	The focus of this project will be to develop an inorganic/polymer composite membrane consisting of a thin, selective inorganic layer embedded in a polymer structure. These technologies provide the potential for high permeance and selectivity, significantly reducing capital and operating costs. Specifically, functional hybrid membranes will be synthesized using a continuous fabrication machine and tested with simulated flue gas.

CARBON STORAGE

FE's Carbon Storage subprogram consists of four Technology Areas: **GEOLOGIC STORAGE TECHNOLOGIES AND SIMULATION AND RISK ASSESSMENT**; **MONITORING, VERIFICATION, ACCOUNTING, AND ASSESSMENT**; **CARBON USE AND REUSE**; and **INFRASTRUCTURE (REGIONAL CARBON SEQUESTRATION PARTNERSHIPS [RCSP])**, all of which are addressing the critical challenges associated with geologic storage. These four Technology Areas sponsor applied research at laboratory scale, validate promising technologies at pilot scale, and support large-scale, large-volume injection field projects at pre-commercial scale to confirm system performance and economics. Within each Technology Area, specific challenges or uncertainties have been identified, and research pathways have been constructed to address these challenges. The first three areas represent the core R&D efforts where projects are carried out from the laboratory to prototype scale. Infrastructure projects (RCSPs and other small- and large-volume field tests), where validation of various geologic storage technology options and their efficacy are being confirmed, represent the development of the storage infrastructure necessary for mass deployment of geologic storage.

The Department's Carbon Storage subprogram goals are the following:

- Develop and validate technologies to ensure 99 percent storage permanence.
- Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent
- Develop technologies to improve reservoir storage efficiency while assuring containment effectiveness.
- Develop Best Practice Manuals (BPMs) for monitoring, verification, accounting (MVA), and assessment; site screening, selection, and initial characterization; public outreach; well management activities; and risk analysis and simulation.

Achieving these goals will require an improved understanding of CO_2 flow and trapping mechanisms within the geologic formations as well as improved technologies for reservoir engineering, monitoring, well construction, and operations. Many of these technologies are applicable to storage with and without enhanced hydrocarbon recovery.

CARBON STORAGE

GEOLOGIC STORAGE TECHNOLOGIES AND SIMULATION AND RISK ASSESSMENT

DOE's Geologic Storage Technologies and Simulation and Risk Assessment (GSRA) Technology Area research effort is developing new understanding of the storage capacity and containment effectiveness of different geologic formations, along with methods to assess and mitigate risks to provide a high level of confidence that injected CO_2 remains permanently stored in geologic storage formations.

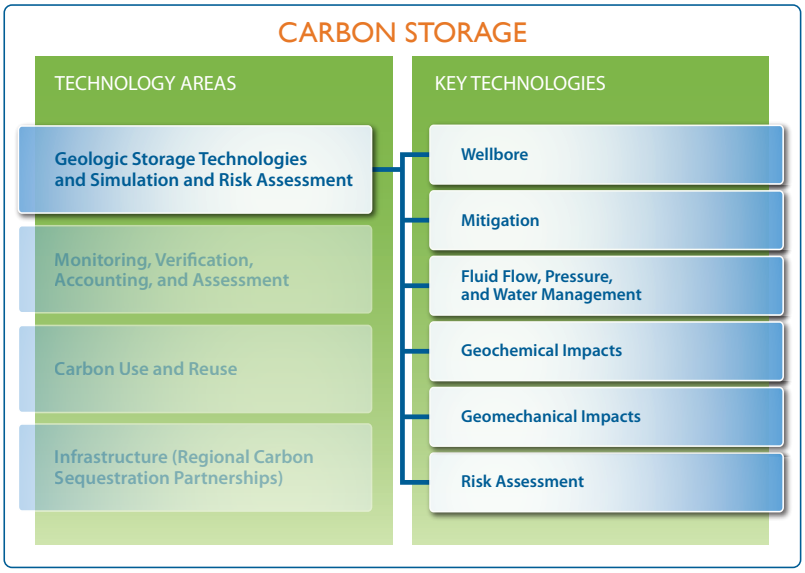


Figure 20. GSRA Key Technologies

Targets

The GSRA Technology Area supports the achievement of GPRA Endpoint Performance Target 3—*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.*

Benefits

Results of GSRA studies will decrease uncertainty in the storage resource potential in the United States and provide a basis for selection of optimum storage sites in different geologic environments. GSRA tools and techniques will improve injection operations and reservoir storage efficiency, and will assure permanent storage at lower cost. GSRA methods also provide the capabilities to assess and mitigate any potential releases.

Critical Challenges

- Improving material and construction techniques to ensure long-term integrity of wellbores exposed to CO_2.
- Mitigation techniques for existing wellbores.
- Improvement of field methods to optimize storage capacity and ensure containment.
- Enhanced simulation tools to improve predictions and enhance performance of geologic storage.

Projects Assessed

The TRLs of 44 projects were assessed in the GSRA Technology Area: 4 in Wellbore; 4 in Mitigation; 22 in Fluid Flow, Pressure, and Water Management; 10 in Geochemical Impacts; 1 in Geomechanical Impacts; and 3 in Risk Assessment. This collective body of work is being pursued to expand the state of knowledge and strengthen the technical basis for the ongoing and planned research in this area.

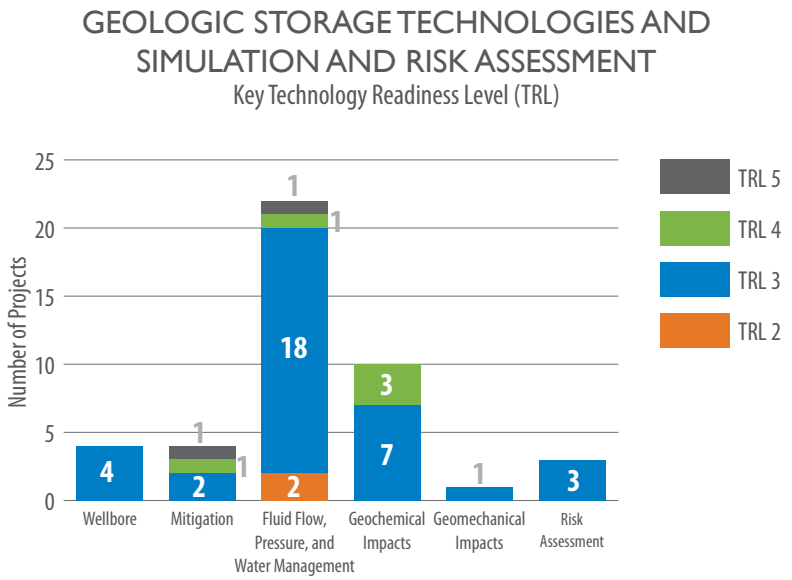


Figure 21. TRL Scores for GSRA Projects

Rating Summary

The critical technology challenges related to GSRA require a portfolio of technologies encompassing the six key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the GSRA technology emerges as a range of TRL values. The overall readiness of the GSRA Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 2 to 5.

Technology Readiness Level Range for Geologic Storage Technologies and Simulation and Risk Assessment

2–5

GEOLOGIC STORAGE TECHNOLOGIES AND SIMULATION AND RISK ASSESSMENT

KEY TECHNOLOGIES

WELLBORE

Wellbores provide access to the deep subsurface for injection of CO_2 and for monitoring. Pre-existing wellbores may be present at some storage sites. Proper materials and construction techniques, coupled with methods to ensure performance, are necessary to ensure safe and reliable injection operations and long-term containment, while at the same time optimizing injection rates.

Four projects within the Carbon Storage GSRA portfolio focused on improving wellbore technologies were assessed. The current TRL of this key technology is 3 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

4 PROJECTS

3 TRL RANGE

MITIGATION

Permanent CO_2 storage relies on the presence of a competent geologic confining zone that will retain the CO_2 for millennia. Penetrations, such as wellbores, and naturally occurring features such as faults and fractures offer potential release pathways for CO_2 to migrate to the surface or to an underground source of drinking water and negate the benefits of removing the CO_2 from the atmosphere. Mitigation technologies are necessary to ensure that any possible releases through these pathways can be addressed.

Four projects within the Carbon Storage GSRA portfolio focused on improving mitigation technologies were assessed. The current TRLs of this key technology ranged from 3–5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

4 PROJECTS
3–5 TRL RANGE

FLUID FLOW, PRESSURE, AND WATER MANAGEMENT

Carbon dioxide injected into the subsurface will need to move, or flow, through the fabric of microscopic and macroscopic pores and fractures that is inherent to storage formations and varies according to the type or rock, depositional environment, and geologic history of the site. Computer simulations of the CO_2 flow and concomitant pressure increases are used to design injection operations and form the basis for methods to optimize injection rates and efficiently use the reservoir storage space. Flow of the CO_2 displaces water. In some circumstances, removal of water may be required to keep pressures within operational limits.

Twenty-two projects within the Carbon Storage GSRA portfolio focused on improving fluid flow, pressure, and water management technologies were assessed. The current TRL of this key technology spans a range of 2–5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

22 PROJECTS
2–5 TRL RANGE

GEOCHEMICAL IMPACTS

CO_2 will react with minerals and brines in the storage formation, and these reactions will have impacts on the movement of the CO_2 during and after injection and its eventual permanent entrapment in the storage formation. Computer simulations of chemical processes are used in conjunction with CO_2 flow simulations to design injection operations and methods to optimize injection rates, efficiently use the reservoir storage space, and ensure containment.

Ten projects within the Carbon Storage GSRA portfolio aimed at improving capabilities to assess geochemical impacts were assessed. The current TRLs of this key technology range from 3–4 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

10 PROJECTS
3–4 TRL RANGE

GEOMECHANICAL IMPACTS

Injection of CO_2 may result in geomechanical deformation in the reservoir, seal, and wellbore, depending on the type of rock, presence of fractures or faults, and the tectonic stresses at the site. Computer geomechanical simulations are carried out to ensure that undesirably large movements do not occur and are used in conjunction with CO_2 flow simulations to design injection operations and methods to optimize injection rates and ensure containment.

One project within the Carbon Storage GSRA portfolio aimed at improving capabilities to assess geomechanical impacts was assessed. The current TRL of this project is 3 for the ongoing work, consistent with the status of the individual technologies embedded within this project.

1 PROJECT
3 TRL RANGE

RISK ASSESSMENT

Risk assessment is being applied broadly in geologic CO_2 storage projects to understand and mitigate an array of potential impacts on, and from, a project. Risk analysis techniques involve identification of potential project risks, determination of the probability of the occurrence of an event and its impact, and identification of actions to control and mitigate risk.

Three projects within the Carbon Storage GSRA portfolio focused on improving risk assessment technologies were assessed. The current TRL of this key technology is 3, consistent with the status of the individual technologies embedded within these projects.

3 PROJECTS
3 TRL RANGE

GEOLOGIC STORAGE TECHNOLOGIES AND SIMULATION AND RISK ASSESSMENT

PORTFOLIO

Table 12. **Geologic Storage Technologies and Simulation and Risk Assessment Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Wellbore			
Battelle Memorial Institute **FE0009367**	Systematic Assessment of Wellbore Integrity for Geologic Carbon Storage Projects Using Regulatory and Industry Information	3	This project focuses on the evaluation of wellbore integrity through statistical analysis. This project is evaluating the risk of well failure and therefore is improving our understanding of potential leakage of CO_2 from carbon storage projects, thereby contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project will develop a short-list of oil/gas, gas storage, or injection wells in the Appalachian and Michigan Basins for a detailed assessment of well history and to collect sustained casing pressure and mechanical integrity test data. Rather than focusing on a specific aspect of wellbore integrity, the project is designed to develop technology to account for wellbore issues from field evaluation to CO_2 storage field siting, to mitigation measures for compromised wellbores. Technical items such as cement degradation, cracks and microannulus, acid-gas zones, channeling, casing corrosion, wellhead leaks, and sustained annulus presssures were evaluated with historical well records, field monitoring of selected gas storage wells, and review of regulatory information.
Clemson University **FE0004542**	Proof of Feasibility of Using Wellbore Deformation as a Diagnostic Tool to Improve CO_2 Sequestration	3	This project focuses on the feasibility of using wellbore deformations to assess the changing conditions of geologic storage formations, confining zones, and well boreholes. Project results should improve the characterization of geologic storage formations, confining zone compressibility, and pressure-dependent permeability and may allow the prediction of the formation or propagation of faults and fractures near a wellbore as well as catastrophic wellbore collapse. This will contribute to improved storage techniques thus reducing CO_2 emissions to the atmosphere. Specifically, this project achieves its targets via improved well borehole characterization, including improvements in the understanding of the bond and integrity between the well casing, the cemented or grouted well annulus (the space between the well casing and the perimeter of the borehole), and the geologic formation itself.
Los Alamos National Laboratory **FWP-FE-302-12-FY14.1**	Sequestration Activities—Task 1: Wellbore and Seal Integrity, Analysis of the Geomechanical Integrity of Wellbores	3	This project is focused on development of improved understanding of the impact of CO_2 on wellbore and caprock integrity. Improved understanding of wellbore stability and caprock performance will allow project developers to more confidently ensure that the CO_2 is permanently stored and improved understanding of the impact of CO_2 on wellbore and caprock integrity will contribute to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, this project will address the chemical and mechanical stability of the cement-caprock and cement-steel bonds in wells and fractures in caprock through a combination of field studies, experimental studies, and numerical modeling.
University of Louisiana at Lafayette **FE0009284**	Statistical Analysis of CO_2 Exposed Wells to Predict Long-Term Leakage Through the Development of an Integrated Neural-Genetic-Algorithm	3	This project focuses on the development of novel hybrid model of a neural-genetic algorithm to perform risk analysis by identifying wells in the Texas Gulf Coast area that should be subjected to remedial action. This project is thereby contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, these efforts will improve our understanding of CO_2 leakage by the use of novel statistical neural-genetic-algorithm methods on general well attributes to predict potential leakage risk.

Table 12. **Geologic Storage Technologies and Simulation and Risk Assessment Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Mitigation			
Montana State University **FE0004478**	Advanced CO_2 Leakage Mitigation Using Engineered Biomineralization Sealing Technologies	4	This project focuses on the study of biomineralization processes that will be effective at sealing flow or leakage pathways near wellbores in subsurface environments. Improved monitoring will contribute to improved storage techniques thus reducing CO_2 emissions to the atmosphere. Specifically, this project achieves its targets via an engineered biomineralization process that, in turn, produces biofilm and mineral deposits that reduce the permeability of geologic media while modifying the geochemistry of brines to enhance CO_2 solubility and mineral precipitation.
Montana State University **FE0009599**	Field Test and Evaluation of Engineered Biomineralization Technology for Sealing Existing Wells	5	This project is focused on developing and field testing a biomineralization technology for sealing small-aperture potential leakage pathways beyond the wellbore. New methods for sealing potential leakage pathways will allow project developers to more confidently ensure that the CO_2 is permanently stored, and improved mitigation and remediation technologies will contribute to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, 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.
University of New Mexico **FE0009562**	Wellbore Seal Repair Using Nanocomposite Materials	3	This project focuses on examining ways to repair leakage pathways by modifying cements with various nanomaterials and polymers. The outcome will be an evaluation of the ability of the nanocomposite materials to repair flaws within the wellbore thereby contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project will contribute to better storage technology by increasing the ability of the well repair material to withstand supercritical CO_2.
University of Texas at Austin **FE0009299**	Novel Materials for Robust Repair of Leaky Wellbores in CO_2 Storage Formations	3	This project focuses on the development of a novel application of a pH-triggered polymer gelant to seal leakage pathways associated with existing wellbores. This project will enhance remedial operations associated with wellbore leakage, thereby contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project will test a novel pH-triggered polymer gelant to determine both its capability for injection directly into leakage pathways typically encountered in wells with poor zonal isolation and for its ability to resist the flow of CO_2-rich fluids.
Key Technology—Fluid Flow, Pressure, and Water Management			
Advanced Resources International, Inc. **FE0010554**	Commercial-Scale CO_2 Injection and Optimization of Storage Capacity in the Southeastern United States	3	This project is focused on addressing knowledge gaps specific to the design and implementation of commercial-scale CO_2 storage projects. Resolution of such issues allows project developers to more confidently predict storage capacity and ensure storage efficiency and permanence, contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project will develop a detailed commercial-scale geologic model, simulate CO_2 injection operations in multiple reservoir scenarios, develop optimized costing scenarios, complete supplemental caprock core analysis, develop new storage efficiency factors that account for geomechanics, and develop simplified screening models capable of rapidly approximating project results.
Argonne National Laboratory **FWP-49607.3**	Management of Water from CCS—Task 3: Lifecycle Water Consumption for CCS	3	This project focuses on evaluating improvements in injectivity of a CO_2 repository by considering water removal options. Water removal reduces reservoir pressure and improves injectivity, resulting in improved storage efficiency and a reduction in CO_2 emissions. Specifically, this project determines environmental costs and benefits by using a process lifecycle assessment approach for net carbon sequestration, net water consumption/production, and total energy consumption.
Battelle Memorial Institute **FE0009051**	Simplified Predictive Models for CO_2 Sequestration Performance Assessment	3	This project focuses on the simulation of CO_2 injection and migration over very large areas. This project is improving our understanding of carbon storage capacity estimation, permanence, and efficiency through the development and validation of a portfolio of simplified modeling approaches to predict the extent of CO_2 plume migration, brine movement, and pressure impact for a semi-confined system with vertical layering, contributing to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, this research will provide project developers with tools to quickly and easily screen candidate storage sites and better identify site-specific monitoring needs.
Fusion Petroleum Technologies **FE0004510**	Experimental Design Applications for Modeling and Assessing Carbon Dioxide Sequestration in Saline	3	This project focuses on the evaluation of various factors (e.g., heterogeneity, reactions, faults, seal integrity) affecting the characterization, design, and operation of saline aquifer storage sites. Improved characterization, design, and operation of saline aquifer sites reduce the risk of fugitive CO_2 emissions and increase confidence in storage permanence. Specifically, this project is evaluating factors affecting storage permanence using modeling (uncertainty analyses and response surface methods), resulting in more cost-effective CO_2 storage.

Table 12. **Geologic Storage Technologies and Simulation and Risk Assessment Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Lawrence Berkeley National Laboratory **FWP-ESD09-056.2**	Consolidated Sequestration Research Project—Task 2: GEO-SEQ	5	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. This project also leverages scientific understanding and technology development through highly visible, ongoing, world-class projects, thereby contributing to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, these efforts will improve current monitoring methods by investigating fundamental geochemical and petrophysical processes that underpin CCS projects using demonstration-scale pilots as testing facilities to scale-up from laboratory to field scale.
Lawrence Berkeley National Laboratory **FWP-ESD09-056.4**	Consolidated Sequestration Research Project—Task 4: Simulation Studies	3	This project focuses on comparison and evaluation of modeling and simulation activities performed that are relevant to carbon storage reservoirs. It enables model uncertainties to be evaluated and their impacts assessed, as well as to improve future modeling efforts by making lessons learned and improvements made by one research team available to other research teams, thereby contributing to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, these efforts will improve current modeling methods and the validation of models by use of field data.
Lawrence Livermore National Laboratory **FWP-FEW0174.1**	Advancing the State of Geologic Sequestration Technologies Toward Commercialization—Task 1: Fresh Water Generation from Aquifer Pressured Carbon Storage	3	This project focuses on the potential for using brine pressurized by CO_2 injection operations in saline formations as the feedstock for desalination and water treatment technologies, including nanofiltration and reverse osmosis. This process improves current storage methods by providing additional storage capacity in the reservoir, thereby contributing to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, this method uses the energy required to inject CO_2 into the subsurface to provide all or part of the inlet pressure for the desalination system.
Lawrence Livermore National Laboratory **FWP-FEW0174.4**	Advancing the State of Geologic Sequestration Technologies Toward Commercialization—Task 4: Snøhvit CO_2 Storage Project	3	This project focuses on developing improved methods to predict and monitor reservoir pressure changes and brine migration and their potential impacts. Improved subsurface monitoring of pressure and brine migration due to CO_2 injection allows project developers to more confidently ensure that CO_2 is permanently stored without adverse impacts, and improved monitoring will contribute to better storage technology and thus reduce CO_2 emissions to the atmosphere. Specifically, this project is researching the geomechanical effects of injection on rock deformation and fault leakage hazards at Snøhvit, and developing a monitoring program focused on potential CO_2/brine migration.
Leland Stanford Junior University **FE0009260**	An Advanced Joint Inversion System for Carbon Dioxide Storage Modeling with Large Date Sets for Characterization and Real-Time Monitoring Enhancing Storage Performance and Reducing Failure Risks Under Uncertainties	3	This study is focused on development of an advanced joint inversion tool, incorporating modeling and monitoring data, which can be used for decision-making for optimal control of CO_2 injection operations. Improved injection control systems allow project developers to more confidently predict storage capacity and ensure storage efficiency and permanence, contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project will improve computational efficiency of stochastic joint inversion, which links forward simulation, dynamic monitoring and inversion, uncertainty quantification (UQ), and risk assessment under a consistent framework.
NETL-ORD **FWP-2012.02.00.2**	ORD Base Carbon Storage—Task 2: Reservoir and Seal Performance	2	This study is focused on performing laboratory experiments and developing a geochemical model addressing CO_2 interactions with brine and caprock. A better understanding of CO_2-brine-rock interactions will enable project developers to more confidently ensure storage efficiency and permanence, contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project is analyzing the sensitivity of geochemical models of subsurface carbon storage to key mineral precipitation and dissolution rates that are occurring at the brine/reservoir/caprock interface where transport is mainly by diffusion.
NETL-ORD **FWP-2012.02.00.4**	ORD Base Carbon Storage—Task 4: Resource Assessments and Geospatial Resources	3	This project focuses on refining methodologies for calculation of CO_2 storage resource in all types of storage formations. Improved storage resource methodologies will enable project developers to more confidently predict storage capacity and ensure storage efficiency, contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project will carry out laboratory measurement and analytic analyses to refine or develop resource assessment methodologies for shale, oil and gas, and saline storage formations.

Table 12. **Geologic Storage Technologies and Simulation and Risk Assessment Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
New Mexico Institute of Mining and Technology **FE0004844**	Nature and Dynamics of the Reservoir/Caprock Contact and Implications for Carbon Storage Performance	3	This project focuses on the detailed analysis and assessment of the interface zone, which includes the top of the storage formation and the bottom of the confining formation. This project will improve monitoring capabilities by using information obtained from rock outcroppings and core samples of proposed CO_2 clastic formations and overlying mudstone-confining zones to determine the characteristics of the interface zone, contributing to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, the project is using these data to develop conceptual models of the behavior of formation-confining zone interfaces and, in particular, sandstone/mudstone contacts.
Trustees of Colorado School of Mines **FE0004630**	Validation of Models Simulating Capillary and Dissolution Trapping	3	This project focuses on the development, validation, and improvement of geological storage models. Improved monitoring will contribute to improved storage techniques thus reducing CO_2 emissions to the atmosphere. Specifically, this project achieves its target of supporting industries' ability to predict geologic storage capacity to within +/-30 percent and to ensure storage permanence by using data generated in intermediate-scale laboratory test systems, which simulate capillary and dissolution trapping under various heterogeneous conditions.
Trustees of Princeton University **FE0009563**	Model Complexity and Choice of Model Approaches for Practical Simulations of CO_2 Injection, Migration, Leakage, and Long-Term Fate	3	This project is focused on developing and assessing the applicability of reservoir process models having different degrees of complexity. Use of models of appropriate complexity will enable operators to more efficiently and confidently predict storage capacity and ensure storage efficiency and permanence, contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project will develop a suite of models having a broad range of complexity and test them against each other in actual field injection cases in order to assess the degree to which models can be used to address design and optimization issues associated with placement and scheduling of injection, extraction, and observation wells.
University of Illinois **FE0009612**	Assessing Reservoir Depositional Environments to Develop and Quantify Improvements in CO_2 Storage Efficiency	3	This project focuses on the development of strategies for improving CO_2 storage efficiency in the presence of geologic heterogeneity and architecture common to reservoirs within specific geologic formation classes. The project will improve our understanding of carbon storage capacity estimation, contributing to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, the project will use rigorously developed geologic and reservoir models representing different potential formation classes and the models will also be generalized for use in sedimentary basins throughout North America.
University of Kansas Center for Research **FE0004566**	Prototype and Testing a New Volumetric Curvature Tool for Modeling Reservoir Compartments and Leakage Pathways in the Arbuckle Saline Aquifer: Reducing Uncertainty in CO_2 Storage and Permanence	3	This project focuses on the evaluation of the effectiveness of a seismic tool (volumetric curvature analysis) to identify the presence, extent, and impact of paleokarst compartments and faulting structures in the Arbuckle Group. Identification of these potentially conductive, through-going fault systems is important for reducing risks associated with carbon storage operations, especially the risk of CO_2 or saline formation fluids migrating into freshwater aquifers. This project will contribute to improved storage and characterization techniques thus reducing the risk of CO_2 emissions to the atmosphere. Specifically, this project achieves its targets by analyzing the seismic data and confirming the presence of identified paleokarst features via horizontal test boring that intersects the paleokarst compartments and boundaries. This may result in a tool that has the potential to be cost-effective for helping to assess geologic storage capacity and CO_2 flow.
University of North Dakota **FE0009114**	Optimizing and Quantifying CO_2 Storage Resource in Saline Formations and Hydrocarbon Reservoirs	2	This project focuses on the development and refinement of the field methods used to quantify and optimize CO_2 storage resources in all major storage reservoir classes. This project is improving our understanding of carbon storage capacity estimation by building geologic models based on field data, performing simulations in different reservoir classes, and refining the storage coefficients and terms used to estimate storage resource in both saline formations and hydrocarbon reservoirs thereby contributing to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, these efforts will improve the current methods and storage coefficients used to calculate storage resource by addressing local and regional pressure effects as well as expanding on the effects that heterogeneity has on the storage resource.
University of Texas at Austin **FE0004956**	Area 1: Influence of Local Capillary Trapping on Containment System Effectiveness	3	This project focuses on the development of a methodology to identify and quantify the extent of capillary trapping of CO_2 in heterogeneous geologic storage formations. Extensive capillary trapping of CO_2 provides confidence that storage is permanent. Specifically, this project is conducting laboratory experiments and performing numerical simulations to assess the extent and location of trapping in geologic repositories thereby reducing the risks associated with long-term CO_2 storage.

Table 12. **Geologic Storage Technologies and Simulation and Risk Assessment Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
University of Texas at Austin **FE0004962**	Area 2: Inexpensive Monitoring and Uncertainty Assessment of CO_2 Plume Migration	3	This project focuses on the development of a prototype of a new computational approach for monitoring the location of CO_2 plumes during injection that is based on pressure and injection rate data. This approach allows for other types of data, such as surface deflection or seismic imaging, to be easily included with the rate/pressure data, which, in turn, will reduce the uncertainty of the inferred plume location and improve monitoring capabilities by improving the ability to predict the expected plume location, contributing to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, The software will be tested on synthetic data sets and validated with field data obtained from CO_2 injection projects.
University of Texas at Austin **FE0009301**	Enhanced Analytical Simulation Tool (EASiTool) for CO_2 Storage Capacity Estimation and Uncertainty Quantification	3	This project is focused on development of an analytical simulation tool EASiTool for CO_2 storage capacity estimation and uncertainty quantification. Development of improved reservoir modeling tools will enable project developers to more confidently predict storage capacity and ensure storage efficiency and permanence, contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project will develop EASiTool, which includes a solution for pressure-buildup calculations, a simple geomechanical model coupled with a base model for rock deformation, and a net-present-value-based optimization algorithm that is a methodology for selecting the optimal number of required injection and extraction wells and new capacity and injectivity estimates under the brine-extraction process.
University of Wyoming **FE0004832**	Maximization of Permanent Trapping of CO_2 and Co-Contaminants in the Highest-Porosity Formations of the Rock Springs Uplift	4	This project focuses on improving our understanding of mixed supercritical CO_2 storage in the Rock Springs Uplift. Better understanding of CO_2 interactions with rock/brine and migration reduces uncertainty in predicting storage capacity and repository suitability. Specifically, this project is determining the technical and economical feasibility of CO_2 storage in the target formation by developing a regional dynamic model.
University of Wyoming **FE0009202**	Optimizing Accuracy of Determinations of Carbon Dioxide Storage Capacity and Permanence, and Designing More Efficient Carbon Dioxide Storage	3	This project focuses on advancing the characterization and assessment of the Rock Springs Uplift in Wyoming as a carbon storage resource. This project is improving estimates of CO_2 storage reservoir capacity, evaluating the long-term integrity and performance of confining layers, and managing injection to optimize CO_2 storage efficiency, thereby contributing to better storage technology thus reducing CO_2 emissions to the atmosphere. A project objective focuses on the sealing characteristics and 3-D interval heterogeneity of the Paleozoic and Mesozoic confining layers. Improving the efficiency of potential storage operations by designing an optimal coupled CO_2 injection/brine production strategy that ensures effective pressure management within the formation is another project objective.
Key Technology—Geochemical Impacts			
Advanced Resources International, Inc. **FE0001560**	The Coal-Seq III Consortium: Advancing the Science of CO_2 Sequestration in Coal Seam and Gas Shale Reservoirs	3	This project focuses on the technical/economic feasibility and application potential of carbon storage in coal seams. This project is improving our understanding of carbon storage capacity estimation in coal seams, contributing to better storage solutions thus reducing CO_2 emissions to the atmosphere. Specifically, this project is focusing on the development and testing of three advanced geochemical and geomechanical modules that will increase the accuracy of simulating CO_2 behavior in coals and shales, coupling these with flow simulation and also addressing coal storage factors such as permeability enhancement, matrix swelling and shrinking, and competition with water as an adsorbed phase on coals, as well as other aspects of CO_2 storage.
Colorado School of Mines **FE0000988**	Simulation of Coupled Processes of Flow, Transport, and Storage of CO_2 in Saline Aquifers	4	This project focuses on development of an improved reservoir simulator to quantitatively model and assess impacts of nonisothermal, multiphase flow and long-term behavior of CO_2 in saline formations. Improved reservoir simulation allows project developers to more confidently predict storage capacity and ensure that the storage formation is being efficiently utilized, and the CO_2 is permanently stored thus reducing CO_2 emissions to the atmosphere. Specifically, this project will develop a parallelized, coupled, multiphase flow and geochemical processes code for CO_2-brine systems.
Lawrence Livermore National Laboratory **FWP-FEW0174.5**	Advancing the State of Geologic Sequestration Technologies Toward Commercialization—Task 5: Enhanced Porosity and Permeability Within Carbonate CO_2 Storage Reservoirs: An Experimental and Modeling Study	4	This project focuses on the calibration of key parameters in reactive transport models that will be used to predict final storage of CO_2 in carbonate EOR fields. This project will advance science-based forecasting for the transition of CO_2-EOR operations to storage sites, thereby contributing to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, these efforts will improve current modeling methods via model calibration against existing experimental data on carbonate rocks from the Midale-Weyburn storage project and experimental and characterization data at larger scales.

Table 12. **Geologic Storage Technologies and Simulation and Risk Assessment Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Pacific Northwest National Laboratory **FWP-58159.1**	Capture and Sequestration Systems Support—Task 1: Sequestration in Basalt Formations	3	This project focuses on research needed to address commercial-scale injection strategies, CO_2 fate and transport, and improved seismic imaging methods for the characterization of basalt formations. Studies using multicomponent gases and different basalts will continue, developing a better understanding of mineralization of basalt formations, thereby contributing to better understanding of geologic storage thus potentially reducing CO_2 emissions to the atmosphere. Specifically, work will continue to build and expand the knowledge base associated with the addition of several newly developed and unique in situ characterization techniques designed to obtain kinetic rate data on important basalt minerals.
Pacific Northwest National Laboratory **FWP-58159.2**	Capture and Sequestration Systems Support—Task 2: Co-Sequestration	3	This project focuses on a multidisciplinary approach for identifying key storage opportunities in depleted shale gas and shale oil reservoirs. Successful storage of CO_2 contributes to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, these efforts will improve current storage methods by (1) identifying R&D needs and pursuing R&D on promising low-cost technologies for utilizing CO_2 in depleted shale gas and shale oil reservoirs and (2) phase behavior and fate and transport of supercritical gas mixtures in fractured geologic formations, (3) casing material studies with water and mixed gas systems, and (4) development of acoustically responsive contrast agents for enhanced monitoring of injected CO_2.
Paulsson, Inc. **FE0004522**	Development and Test of a 1,000-Level 3C Fiber-Optic Borehole Seismic Receiver Array Applied to Carbon Sequestration	4	This project focuses on characterization of storage sites and tracking of CO_2 in the subsurface by designing, building, and testing a next-generation downhole seismic system. Improved site characterization CO_2 tracking enables an operator to more confidently demonstrate that the storage formation is being efficiently utilized and that the CO_2 is permanently stored. Specifically, the project is employing fiber-optic seismic sensor technology deployed on drill pipe to provide enhance, high-resolution, seismic imaging technology. Improved site characterization will contribute to better storage techniques thus reducing CO_2 emissions to the atmosphere.
Trustees of Indiana University **FE0004381**	Reducing Uncertainties in Model Predictions Via History Matching of CO_2 Migration and Reactive Transport Modeling of CO_2 Fate at the Sleipner Project, Norwegian North Sea	3	This project is focused on using history matching and the 4-D seismic reflection imaging at Sleipner in the North Sea to reduce the uncertainty in understanding the impacts of CO_2 and reactive transport in saline formations. Reduction of uncertainty in reactive transport modeling allows project developers to more confidently predict storage capacity and ensure that the storage formation is being efficiently utilized. In addition, it provides confidence that the CO_2 is permanently stored, thus contributing to better storage technology and reducing CO_2 emissions to the atmosphere. Specifically, this project is conducting multiphase flow and reactive transport modeling of CO_2 migration within the Utsira Sandstone at the Sleipner project. The model is calibrated through history matching using the progressive CO_2 plume migration delineated by the 4-D seismic data, to predict at a regional scale, the CO_2 fate up to 10,000 years after injection into the reservoir.
University of Utah **FE0009773**	Reactive Transport Models with Geomechanics to Mitigate Risks of Carbon Dioxide Utilization and Storage	3	This project is focused on development of an improved, validated, reservoir simulator for CO_2 storage. Improved simulation of reservoir processes allows project developers to more confidently predict storage capacity and ensure storage efficiency and permanence, contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project will develop a simulator that combines CO_2 reactive transport and reservoir mechanics (pore structure changes due to dissolution and precipitation, and fracturing), with the intention of performing more physics-based simulations and predictions of coupled thermal-hydro-mechanical-chemical behavior due to CO_2 injection.
University of Wyoming **FE0009238**	Optimal Model Complexity in Geological Carbon Sequestration: A Response Surface Uncertainty Analysis	3	This project focuses on assessing how well upscaling and response surface methods represent coupled physical and chemical processes associated with CO_2 storage. Response surface methods and appropriate upscaling have the potential to enable project developers to more confidently predict storage capacity and ensure storage efficiency and permanence, contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project will use a multicomponent-multiphase-multiphysics nonisothermal reactive flow and transport model to assess upscaling and response surface methods applied to sedimentary environments.
Yale University **FE0004375**	Integrated Experimental and Modeling Studies of Mineral Carbonation as a Mechanism for Permanent CS in Mafic/Ultramafic Rocks	3	This project focuses on the key chemical reactions that occur as a result of the injection of CO_2 into ultramafic/basaltic rocks. The chemical reactions under study are also relevant to injection of CO_2 into sedimentary rocks, including saline aquifers and petroleum reservoirs. Improved understanding of these underground reactions will contribute to improved storage techniques thus reducing CO_2 emissions to the atmosphere. Specifically, this project achieves its targets by (1) enhancing the conversion of CO_2 to carbonate minerals (mineral carbonation), and (2) using mineral-fluid-organic reactions that create or reduce porosity and may catalyze the in situ reduction of CO_2 to solid mineral compounds.

Table 12. **Geologic Storage Technologies and Simulation and Risk Assessment Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Geomechanical Impacts			
Massachusetts Institute of Technology **FE0009738**	Enhanced Simulation Tools to Improve Predictions and Performance of Geologic Storage Coupled Modeling	3	This project focuses on the development of tools for improving the modeling and risk assessment of CO_2 permanence in geologic formations. This project is advancing the current baseline modeling and risk assessment technology by developing improved simulation approaches thereby contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, these efforts will improve modeling and risk assessment by applying the models of fault poromechanics and CO_2 migration and trapping to synthetic reservoirs and actual deep formations in the continental United States.
Key Technology—Risk Assessment			
Geomechanics Technologies, Inc. **FE0009168**	Development of Improved Caprock Integrity and Risk Assessment Techniques	3	This project is focused on development of improved methods to assess geomechanical impacts and possible associated risk of caprock integrity problems during geologic storage of CO_2. Improved methods for assessing caprock integrity will allow project developers to more confidently ensure that the CO_2 is permanently stored and improved geomechanical assessments of caprock integrity and risk assessment methods will contribute to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, this project analyzes and describes historical caprock integrity problems experienced in natural gas storage and oil and gas waste injection operations, initiates development of an advanced geomechanical simulation technique to model geomechanical impacts on the caprock, and develops a quantitative risk assessment tool for caprock integrity.
Los Alamos National Laboratory **FWP-FE-302-12-FY14.3**	Sequestration Activities—Task 3: Systems Modeling and Science of CO_2 Sequestration	3	This project focuses on the development of systems modeling capabilities that can be used to evaluate suitability of specific geologic sites for long-term storage of CO_2. The modeling capabilities being developed are focused on (1) addressing issues related to production and treatment of brine to reduce pressure in the reservoir and reduce the risks of induced seismicity and (2) assessing feasibility of CO_2-EOR operations for maximizing CO_2 storage and oil recovery. Additionally, the project also focuses on furthering the state of knowledge of CO_2 leakage in shallow groundwater aquifers and subsequent impacts.
University of Texas at Austin **FE0001563**	Developing a Comprehensive Risk Assessment Framework for Geological Storage of CO_2	3	This project is focused on developing an improved risk assessment framework for geological storage of CO_2. Improved risk assessment methods will allow project developers to more confidently ensure that the CO_2 is permanently stored and improved risk assessment technologies will contribute to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, this project is using Bayesian inference methods, safety records from analogue projects, expert panels, and technical studies of pressure impacts and potential leakage to develop a comprehensive analysis of programmatic and technical risks associated with CO_2 sequestration in deep saline formations.

CARBON STORAGE

MONITORING, VERIFICATION, ACCOUNTING, AND ASSESSMENT

The Monitoring, Verification, Accounting, and Assessment (generally abbreviated by those in the user community as MVA) Technology Area research effort is developing a portfolio of monitoring technologies to provide a high level of confidence that injected CO_2 remains permanently stored in geologic storage formations.

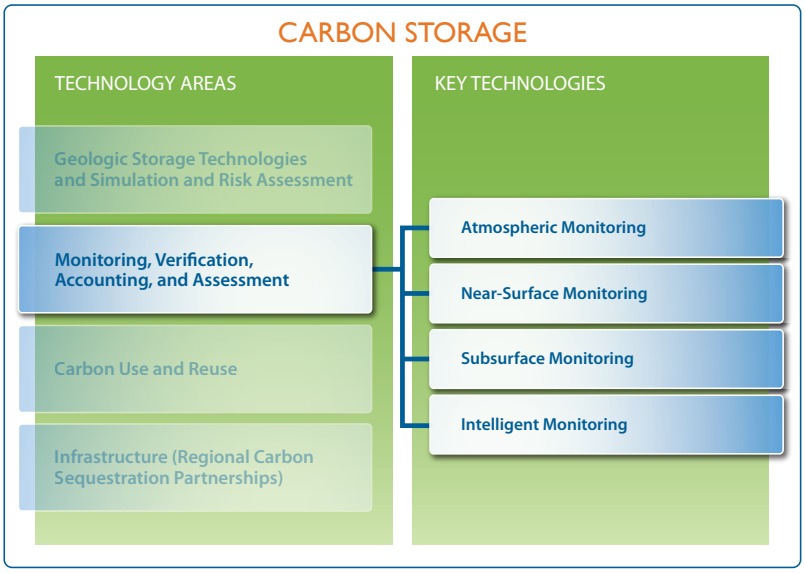


Figure 22. MVA Key Technologies

Targets

The MVA Technology Area supports the achievement of GPRA Endpoint Performance Target 3—*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.*

Benefits

Development of key MVA technologies will enable operators to satisfy EPA operating requirements to ensure that potable groundwater and ecosystems are protected, and EPA monitoring requirements for GHG reporting. MVA efforts are also designed to enable project developers to more confidently predict storage capacity and ensure that the storage formation is being efficiently utilized, both onshore and offshore, through multilevel monitoring programs that are both reliable and cost-effective.

Critical Challenges

- Improve the ability of techniques to detect and quantify any potential CO_2 releases from wellbores or other migration pathways.
- Map the CO_2 and pressure front in the reservoirs in various depositional environments.
- Integrate tools and systems for improved, long-term monitoring.

Projects Assessed

The TRLs of 20 projects were assessed in the MVA Technology Area: 5 in Atmospheric Monitoring, 3 in Near-Surface Monitoring, 11 in Subsurface Monitoring, and 1 in Intelligent Monitoring. This collective body of work is being pursued to expand the state of knowledge and strengthen the technical basis for the ongoing and planned research in this area.

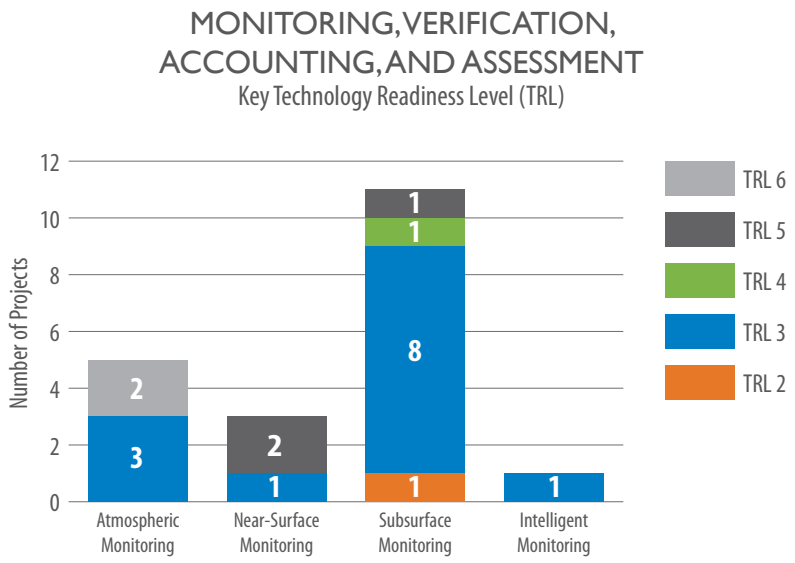


Figure 23. TRL Scores for MVA Projects

Rating Summary

The critical technology challenges related to MVA require a portfolio of technologies encompassing the four key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the MVA technology emerges as a range of TRL values. The overall readiness of the MVA Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 2 to 6.

Technology Readiness Level Range for Monitoring, Verification, Accounting, and Assessment

2–6

MONITORING, VERIFICATION, ACCOUNTING, AND ASSESSMENT

KEY TECHNOLOGIES

ATMOSPHERIC MONITORING

Above-ground CO_2 monitoring provides assurance of storage permanence. Atmospheric monitoring techniques include sensors for CO_2 and natural and injected chemical tracers, airborne gas sensors, eddy covariance, and laser-induced differential absorption radar (LIDAR) techniques.

Five projects within the Carbon Storage MVA portfolio that focus on improving atmospheric monitoring technologies were assessed. The current TRLs of these projects are 3 and 6 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

5
PROJECTS
3–6
TRL RANGE

NEAR-SURFACE MONITORING

Near-surface CO_2 monitoring techniques also provide assurance of storage permanence. In particular, near-surface groundwater monitoring may be required as part of an Underground Injection Control Class VI injection permit. 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. Important information for managing reservoir operations and confirming performance is also provided by (1) satellite imagery for ecosystem-stress monitoring and (2) satellite-based radar for detection of surface deformation.

3 PROJECTS
3–5 TRL RANGE

Three projects within the Carbon Storage MVA portfolio that focus on improving near-surface monitoring technologies were assessed. The current TRLs of these projects are 3 and 5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

SUBSURFACE MONITORING

Monitoring CO_2 in the subsurface is a key component of verifying storage technology performance and long-term containment. Techniques for subsurface monitoring include wireline logging; pressure and temperature sensing; fluid sampling and tracer analysis; and geophysical techniques, including seismic, gravity, and electrical methods. Subsurface monitoring techniques 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. These technologies are being developed for deployment in many different depositional systems, with a focus on determining the geologic conditions in which they will be most effective.

11 PROJECTS
2–5 TRL RANGE

Eleven projects within the Carbon Storage MVA portfolio that focus on improving subsurface monitoring technologies were assessed. The current TRLs of this key technology range from 2–5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

INTELLIGENT MONITORING

Intelligent monitoring systems combine real-time data collection, site-specific and project-specific data analysis and interpretation, and injection control. Such systems need to integrate diverse data from atmospheric, near-surface, and subsurface monitoring networks and convert these data into meaningful and actionable information. Data processing, analysis, and interpretation workflows must be developed that address the particular needs and objectives of an individual storage project. Information delivery and advanced visualization are important components of this key technology.

1 PROJECT
3 TRL RANGE

One project within the Carbon Storage MVA portfolio aimed at developing high-confidence intelligent monitoring systems was assessed. This key technology has a TRL of 3.

MONITORING, VERIFICATION, ACCOUNTING, AND ASSESSMENT

PORTFOLIO

Table 13. **Monitoring, Verification, Accounting, and Assessment Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Atmospheric Monitoring			
ITT Space Systems, LLC **FE0012574**	Greenhouse Gas Laser Imaging Tomography Experiment (Green Lite)	3	This project focuses on the development and testing of a novel system that is capable of detecting CO_2 leaks over large areas being considered for underground carbon storage, up to several square kilometers. Improved surface monitoring will quickly identify where remedial measures are needed to prevent CO_2 emissions to the atmosphere. Specifically, this project achieves its targets via remote active sensing technologies that quantitatively measure atmospheric CO_2 and that can generate two-dimensional (2-D) concentration and flux maps over the entire carbon storage field, which, in turn, will enable CO_2 leaks to be located, quantified and addressed based on real-time web interface.
Los Alamos National Laboratory **FWP-FE-302-12-FY14.2**	Sequestration Activities—Task 2: Development and Deployment of MVA Tools	3	This project focuses on developing more effective atmospheric monitoring of CO_2 injections using isotopes. Development and deployment of advanced monitoring tools contribute to better storage technology and thus reduce CO_2 emissions to the atmosphere. Specifically, this project involves the enhancement of the in situ portion of the frequency-modulation spectroscopy (FMS)-differential absorption LIDAR (DIAL) CO_2 instrument to detect the stable isotopes of CH_4 and H_2S.
Montana State University **FE0001156**	Development and Deployment of a Compact Eye-Safe Scanning Differential Absorption LIDAR for Spatial Mapping of Carbon Dioxide for Monitoring/Verification/Accounting at Geologic Carbon Sequestration Sites	6	This project focuses on monitoring of CO_2 by identifying CO_2 that has potentially escaped confinement. More sensitive methods for detecting fugitive CO_2 in the atmosphere allow geologic storage project developers to confidently quantify the amount of CO_2 permanently stored in geologic repositories. Specifically, this 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.
Oklahoma State University **FE0012173**	Surface and Airborne Monitoring Technology for Detecting Geologic Leakage in a CO_2-Enhanced Oil Recovery Pilot, Andarko Basin, Texas	3	This project focuses on developing surface and airborne technologies for detecting possible CO_2 leakage from storage sites. Better CO_2 near-surface monitoring methods allow project developers to more confidently and cost-effectively ensure that CO_2 is permanently stored and improved monitoring will contribute to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, this project will develop new near-surface and airborne monitoring technologies utilizing infrared gas analyzers, and integrate them with ground-based sampling in order to improve accuracy while minimizing the number of sensors, thereby reducing labor and maintenance costs.
Planetary Emissions Management, Inc. **FE0001116**	Near-Surface Leakage Monitoring for the Verification and Accounting of Geologic Carbon Sequestration Using a Field-Ready 14c Isotopic Analyzer	6	This project focuses on monitoring of fossil-fuel-generated CO_2 by identifying CO_2 that has potentially escaped containment. More sensitive methods for detecting fugitive CO_2 in the atmosphere allow geologic storage project developers to confidently quantify the amount of CO_2 permanently stored. Specifically, this 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 based on Planetary Emissions Management's multi-isotopic global monitor platform.
Key Technology—Near-Surface Monitoring			
Intelligent Optical Systems, Inc. **FE0012706**	Real-Time In Situ Carbon Dioxide Monitoring Network for Sensitive Subsurface Areas in Carbon Capture and Storage	3	This project focuses on developing real-time near-surface monitoring capability for detecting possible CO_2 leakage in groundwater. Better CO_2 near-surface monitoring methods allow project developers to more confidently ensure that CO_2 is permanently stored, and understand impacts on groundwater, should a leak occur, and this improved monitoring will contribute to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, this project will develop a real-time fiber-optic system for the accurate detection of CO_2 and changes in pH, salinity, and temperature in groundwater.
Trustees of Columbia University **FE0001535**	Tagging Carbon Dioxide to Enable Quantitative Inventories of Geological Carbon Storage	5	This project focuses on quantitative method to measure the amount of CO_2 stored by geologic sequestration. More precise measurements allow project developers to confidently quantify the amount of CO_2 permanently stored. Specifically, this 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.

Table 13. **Monitoring, Verification, Accounting, and Assessment Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
University of Miami **FE0001580**	Combining Space Geodesy, Seismology, and Geochemistry for Monitoring, Verification, and Accounting of CO_2 in Sequestration Sites	5	This project focuses on developing a low-cost methodology for determining the fate of injected CO_2. Better CO_2 monitoring methods allow project developers to more confidently quantify the amount of CO_2 permanently stored. Specifically, this 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.
Key Technology—Subsurface Monitoring			
Electric Power Research Institute **FE0012700**	Distributed Fiber-Optic Arrays: Integrated Temperature and Seismic Sensing for Detection of CO_2 Flow, Leakage, and Subsurface Distribution	2	This project focuses on developing and demonstrating a new, improved, seismic geophysics monitoring technology for tracking the CO_2 plume and detecting possible leaks in the subsurface. Improved seismic methods allow project developers to more confidently and cost-effectively ensure that the storage formation is being efficiently utilized and the CO_2 is permanently stored. Improved monitoring will contribute to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, this project will develop and field test a distributed fiber-optic array that integrates both temperature measurement and seismic survey data acquisition.
Lawrence Berkeley National Laboratory **FWP-ESD09-056.3**	Consolidated Sequestration Research Project—Task 3: Fundamental Studies	3	This project focuses on developing new and improved methods to track the CO_2 in the subsurface and detect possible leaks. Improved subsurface monitoring and leak detection methods allow project developers to more confidently ensure that CO_2 is permanently stored, and improved monitoring will contribute to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, this project will develop rock-physics models for improved quantitative interpretation of seismic measurements and conduct distributed-thermal-perturbation-sensor measurements in observation boreholes to validate use of the method for detection of CO_2 in the near-wellbore region.
Multi-Phase Technologies, LLC **FE0012266**	Deep Controlled Source Electromagnetic Sensing: A Cost-Effective, Long-Term Tool for Sequestration Monitoring	3	This project focuses on developing and demonstrating a permanent, autonomous, electrical geophysics monitoring system for tracking the CO_2 plume in the subsurface. A permanent, autonomous monitoring system will allow project developers to more confidently, and cost-effectively, ensure that CO_2 is permanently stored and improved monitoring will contribute to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, this project will develop and field test controlled source electromagnetic methods with a borehole source to measure the electrical properties of CO_2 in the subsurface.
NETL-ORD **FWP-2012.02.00.3**	ORD Base Carbon Storage—Task 3: Monitoring Groundwater Impacts	3	This project focuses on developing methods to use natural geochemical signals for monitoring groundwater impacts associated with possible CO_2 release. Improved methods of groundwater monitoring will enable operators to more confidently ensure storage permanence, contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project will carry out laboratory and field measurements to assess the application of natural isotope tracers (Sr, Fe, Li, U), stable carbon isotopes, and organic compounds as natural geochemical tracers.
NETL-ORD **FWP-2012.02.00.5**	ORD Base Carbon Storage—Task 5: Monitoring CO_2 and Pressure Plume	3	This project focuses on development of improved seismic technology to monitor CO_2 movement in the subsurface. Improved subsurface monitoring technology will enable project developers to more confidently predict storage capacity and ensure storage efficiency and permanence, contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this project will carry out studies to improve double-difference tomography, develop seismic attributes for CO_2 and stress, and validate techniques.
Oak Ridge National Laboratory **FWP-FEAA045**	Monitoring of Geological CO_2 Sequestration Using Isotopes and PF Tracers	4	This project focuses on field studies that utilize natural isotopes and perfluorocarbon (PF) tracers to monitor CO_2 and reservoir conditions and to obtain baseline data on the chemistry of fluids and gases prior to injection at the Southeast Regional Carbon Sequestration Partnership (SECARB), Cranfield site. These data form the foundation upon which evaluation of the hydrodynamic nature of the formation can be performed thereby contributing to better storage technology and thus reducing CO_2 emissions to the atmosphere. Specifically, this information will be integrated into an MVA system model and compared with results from the Frio brine pilot test.
Schlumberger Carbon Services **FE0001040**	Quantification of Wellbore Leakage Risk Using Nondestructive Borehole Logging Techniques	3	This project focuses on developing a new method to evaluate the risk of wellbore leakage. Reducing the risk of wellbore leakage provides greater confidence that the CO_2 in permanently stored. Specifically, this project is formulating correlations related to leakage risk using data obtained from commercial wireline well logging to reduce containment uncertainty and further ensure CO_2 storage permanence.

Table 13. **Monitoring, Verification, Accounting, and Assessment Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Stanford University **FE0001159**	Advanced Technologies for Monitoring CO_2 Saturation and Pore Pressure in Geologic Formations: Linking the Chemical and Physical Effects to Elastic and Transport Properties	3	This project focuses on developing more precise methodology for monitoring CO_2 in the subsurface. Better monitoring methods allow project developers to confidently quantify the amount of CO_2 permanently stored. Specifically, this project improves seismic data interpretation by developing experimentally based, CO_2-optimized rock-fluid models to ensure that injection fields and abandoned wells are not leaking, and to verify the quantity of CO_2 injected.
Trustees of Columbia University **FE0004847**	Radiocarbon as a Reactive Tracer for Tracking Permanent CO_2 Storage in Basaltic Rocks	5	This projects aims to study CO_2 storage in basalts and validate mineral carbonation through use of tracers, fluid sampling, and core drilling and analyses. Fluid and rock samples are collected from a basalt formation in Iceland, where the injected CO_2 has been labeled with the 14C tracer and other tracers. These samples will be analyzed to determine the extent of mineral carbonation that occurs when CO_2 is injected into a basaltic storage reservoir. Specifically, these efforts will improve current storage methods by analyzing fluid samples to characterize the CO_2 dispersion in the basalt. Results are being integrated to assess the use of the tracers for determining reservoir flow and geochemical reactivity, and to assess in situ mineral carbonation in basalt storage formations, thereby contributing to better storage technology thus reducing CO_2 emissions to the atmosphere.
University of North Dakota **FE0012665**	Scalable Automated, Semipermanent Seismic Method for Detecting CO_2 Plume Extent During Geological CO_2 Injection	3	This project focuses on developing and demonstrating a scalable, automated, semipermanent, seismic geophysics method for tracking the CO_2 plume in the subsurface. Improved seismic methods allow project developers to more confidently and cost-effectively ensure that the storage formation is being efficiently utilized and the CO_2 is permanently stored. Improved monitoring will contribute to better storage technology thus reducing CO_2 emissions to the atmosphere. Specifically, this project will develop and demonstrate use of a new impulsive downhole source deployed semipermanently in combination with a sparse surface receiver array approach to track the CO_2 plume edge.
University of Texas at Austin **FE0012231**	Pressure-Based Inversion and Data Assimilation System (PIDAS) for CO_2 Leakage Detection	3	This project focuses on the monitoring of CO_2 in the subsurface by developing a pressure-based inversion data assimilation system. This new pressure-based method is improving an operator's ability to demonstrate that the CO_2 is permanently stored and to detect leakage should it occur. Specifically, this project is demonstrating the utility of harmonic pulse testing and developing inversion algorithms for leakage detection.
Key Technology—Intelligent Monitoring			
West Virginia University Research Corporation **FE0001163**	In Situ MVA of CO_2 Sequestration Using Smart Field Technology	3	This project focuses on data processing and analyses to better determine the location and amount of fugitive CO_2 from geologic repositories. Better resolution of location and amount of fugitive CO_2 allows project developers to better determine CO_2 storage permanence, potential leakage detection, and response. Specifically, this project is developing a software package that autonomously summarizes raw data collected from in situ pressure gauges and prepares those data for processing and analysis to estimate the location and amount of fugitive CO_2.

CARBON STORAGE

CARBON USE AND REUSE

FE's Carbon Use and Reuse Technology Area research effort is developing a portfolio of technologies with the highest potential to help foster the commodity market for CO_2 while making no additional contribution to CO_2 emissions. Research within the Carbon Use and Reuse Technology Areas is focused on using CO_2 as a feedstock in a variety of ways. The current global market for bulk CO_2 is small and most applications do not account for its ultimate fate. CO_2 use and reuse will not replace geologic storage, but will complement the efforts to offset the cost of capture. Some of the applicable technologies involving carbon use and reuse are conversion of CO_2 into useful chemicals and polycarbonate plastics and storage of CO_2 in enhanced concrete products. These technologies are the focus of the FE-supported research effort currently underway.

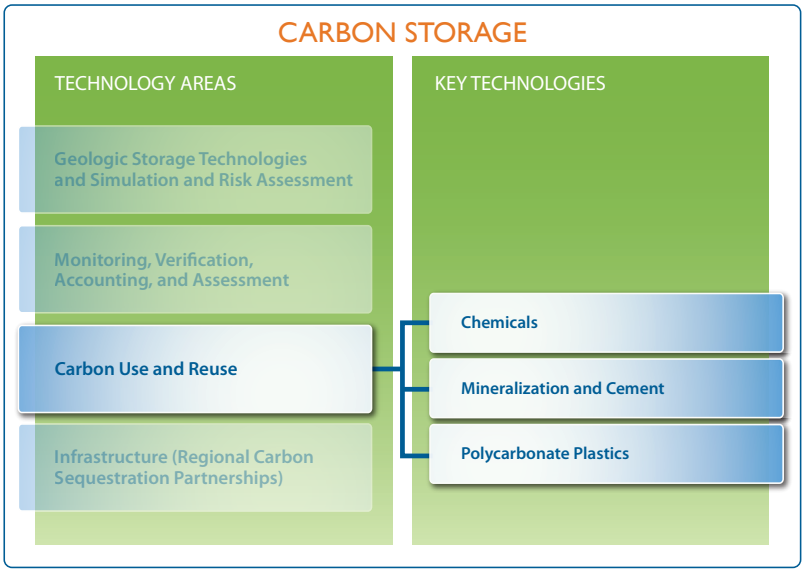


Figure 24. Carbon Use and Reuse Key Technologies

Targets

The Carbon Use and Reuse Technology Area covers a broad spectrum of research with different technical challenges. The goals of the Carbon Storage subprogram are set to achieve successful implementation of various applications at different time horizons. Research is designed for commercialization in the 2035 timeframe; hence many technologies are in the early stages of development.

Benefits

The concept of converting CO_2 to a valued product and possibly accelerating the implementation of carbon capture and storage has attracted interest worldwide. However, a more robust portfolio of opportunities and technologies for creating products from CO_2 is currently being developed.

Critical Challenges

- Cost-effective use of CO_2 as a feedstock for chemical synthesis or its integration into preexisting products.
- Efficiency (CO_2 integration reaction rate and the amount of CO_2 stored in a product) and energy use (the amount of energy required to utilize CO_2 in existing products) of these utilization processes.

Projects Assessed

The TRLs of 4 projects were assessed in the Carbon Use and Reuse Technology Area: 2 in Chemicals and 2 in Mineralization and Cement. This collective body of work is being pursued to expand the state of knowledge and strengthen the technical basis for the ongoing and planned research in this area.

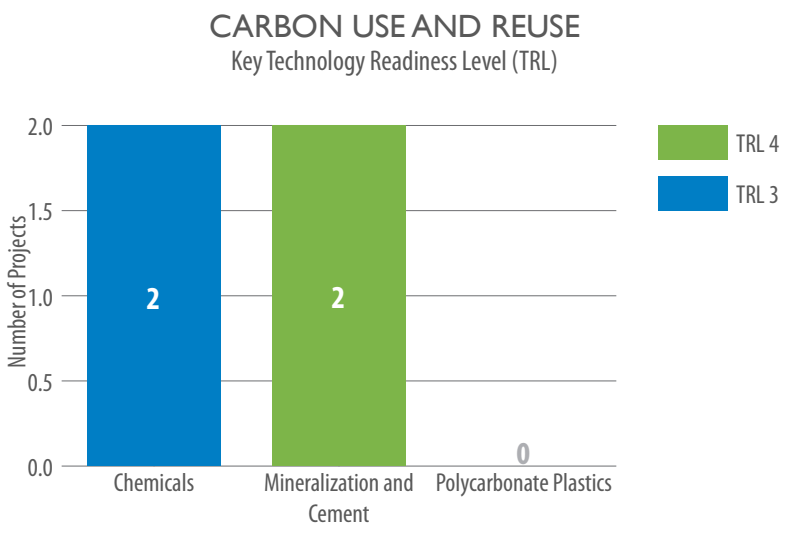


Figure 25. TRL Scores for Carbon Use and Reuse Projects

Rating Summary

The critical technology challenges related to Carbon Use and Reuse require a portfolio of technologies encompassing the three key technologies. For the FY14 assessment, the Polycarbonate Plastics key technology did not include any active projects as defined in the TRL Methodology section. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the Carbon Use and Reuse technology emerges as a range of TRL values. The overall readiness of the Carbon Use and Reuse Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 3 to 4.

Technology Readiness Level Range for Carbon Use and Reuse

3–4

CARBON USE AND REUSE

KEY TECHNOLOGIES

CHEMICALS

Providing CO_2 as a plentiful and inexpensive feedstock to industry could offer opportunities to develop more efficient, less costly, and safer manufacturing processes compared to conventional manufacturing. Greater energy efficiency and CO_2 consumed in the process could reduce net emissions. The research is focused on developing advanced catalysts and/or processes to produce chemicals such as carbon monoxide, formic acid, methanol, and various organic carbonates.

Two projects within the Carbon Storage Carbon Use and Reuse portfolio focused on developing technologies for commodity chemicals were assessed. The current TRL of this key technology is 3, consistent with the status of the individual technologies embedded within these projects.

2
PROJECTS
3
TRL RANGE

MINERALIZATION AND CEMENT

Carbonate mineralization is the conversion of CO_2 to solid inorganic carbonates. Naturally occurring alkaline and alkaline-earth oxides react chemically with CO_2 to produce minerals, such as $CaCO_3$ and magnesium carbonate ($MgCO_3$). Curing concrete and concrete-like materials with CO_2 has the potential to reduce curing time, use less energy, and enhance mechanical properties while consuming CO_2 in the process.

Two projects within the Carbon Storage Carbon Use and Reuse portfolio that focus on improved mineralization/cement technologies were assessed. The current TRL of this key technology is 4, consistent with the status of the individual technologies embedded within these projects.

2 PROJECTS
4 TRL RANGE

POLYCARBONATE PLASTICS

Traditional monomers, such as ethylene and propylene, can be combined with CO_2 to produce polycarbonates, such as polyethylene carbonate and polypropylene carbonate. The advantage of this technology is that it copolymerizes CO_2 directly with other monomers without first converting the CO_2 to carbon monoxide or some other reactive species, thus significantly reducing energy requirements. There are many potential uses for polycarbonate plastics, including coatings and laminates.

No projects under the Polycarbonate Plastics key technology met the TRL assessment requirement (as explained on page 10); therefore zero projects were assessed in this key technology for the FY14 report. One project was completed in FY13 and not included in the assessment. Additional projects may be performed in the future.

0 PROJECTS
N/A TRL RANGE

CARBON USE AND REUSE

PORTFOLIO

Table 14. **Carbon Use and Reuse Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Chemicals			
NETL-ORD **FWP-2012.02.00.6**	ORD Base Carbon Storage—Task 6: Catalytic Conversion of CO_2 to Industrial Chemicals	3	This project focuses on development of materials and reactor technologies for the catalytic conversion of CO_2 to industrial chemicals. Identifying commercial uses for CO_2 that do not generate additional carbon emissions results in reduction of GHG emissions. Specifically, this project will demonstrate conversion of CO_2 to value-added products (methane, methanol, and formic acid), and conduct studies addressing the synthesis, characterization, proof-of-concept, and performance assessment phases associated with the development of catalyst systems. Materials of interest include Cu-oxides, zinc oxide (ZnO), atomically precise clusters (Au_x, Ni_x, Cu_x; $x \approx 10$ to 100), plasmonic catalysts, heterostructured nanomaterials, and other related systems capable of utilizing carbon-friendly energy sources for driving CO_2 reactions.

Table 14. **Carbon Use and Reuse Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Research Triangle Institute **FE0004329**	Conversion of CO_2 into Commercial Materials Using Carbon Feedstocks	3	This project focuses on evaluating the potential for converting CO_2 into a feedstock for industrial processes. Carbon monoxide can be used in producing marketable chemicals thereby reducing GHG emissions. Specifically, this project is conducting carbon reaction experiments in a laboratory and performing simulations to evaluate process economics.
Key Technology—Mineralization and Cement			
McGill University **FE0004285**	Beneficial Use of Carbon Dioxide in Precast Concrete Production	4	This project focuses on the development of a precast concrete curing process that uses CO_2 as a reactant. Commercial uses for this process will store CO_2 with a net reduction of GHG emissions. Specifically, this project is determining the ability of CO_2 to accelerate strength gain, improve durability, and reduce energy consumption and GHG emissions by designing and testing carbonated concrete blocks and fiber-cement panels and performing short-term and long-term evaluation of carbonated products.
Solidia Technologies, Inc. **FE0004222**	Utilization of CO_2 in High-Performance Building and Infrastructure Products	4	This project focuses on developing a process that uses a CO_2-consuming inorganic binder as a substitute for Portland cement in concrete. Commercial uses for this process will sequester CO_2 with a net reduction of GHG emissions. Specifically, this project quantifies the reduction in energy and GHG emissions associated with making Portland cement while sequestering large amounts of CO_2 through a laboratory/engineering process study.

CARBON STORAGE

INFRASTRUCTURE—REGIONAL CARBON SEQUESTRATION PARTNERSHIPS

The Infrastructure Technology Area research effort is carrying out small- and large-scale field tests to demonstrate that different types of geologic storage reservoirs, distributed over different geographic regions of the United States, have the capability to permanently store CO_2, and provide the basis for commercial-scale CO_2 tests. The majority of the Infrastructure effort is conducted by the Regional Carbon Sequestration Partnership (RCSP) network to help develop the technology and infrastructure, to implement large-scale CO_2 storage regionally, and provide the foundation for commercial-scale CO_2 storage. RCSP field tests involve integrated system testing and validation of geologic storage; simulation and risk assessment; and monitoring, verification, and accounting technologies in different depositional environments.

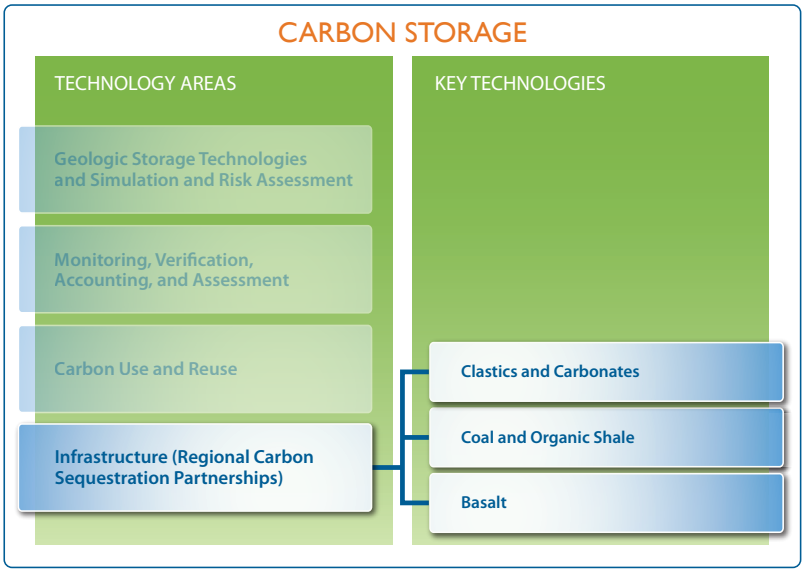


Figure 26. Infrastructure Key Technologies

Targets

The Infrastructure Technology Area supports the achievement of GPRA Endpoint Performance Target 3—*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.*

Benefits

Knowledge and experience gained from small- and large-scale field tests in different depositional environments will confirm that CO_2 injection and storage can be achieved safely, permanently, and economically. Results from these projects will provide a more thorough understanding of processes, methodologies, and risk from site characterization through closure for a carbon storage project. In addition, these projects will reduce uncertainty and increase confidence in understanding of migration and permanent trapping of CO_2 within various reservoir classes of geologic storage formations, which will help support regulatory development and industry in commercialization and deployment of CCS.

Critical Challenges

- Proving adequate injectivity, available storage capacity, and storage permanence across the range of major reservoir classes.
- Developing injection strategies, risk assessment, and monitoring strategies that are best suited for the particular geologic structures, reservoir architectures, and ranges of properties characteristic of each of the 11 major reservoir classes.[1]

1 For definition and description of reservoir classes, see: *Understanding Geologic Storage Formation Classifications—Importance to Understanding and Impacts on CCS Opportunities in the United States*. http://www.netl.doe.gov/File%20Library/Research/Carbon%20Seq/Reference%20Shelf/BPM_GeologicStorageClassification.pdf

Projects Assessed

The TRLs of 11 projects were assessed in the Infrastructure Technology Area: 9 in Clastics and Carbonates and 2 in Coal and Organic Shale. This collective body of work is being pursued to expand the state of knowledge and strengthen the technical basis for the ongoing and planned research in this area.

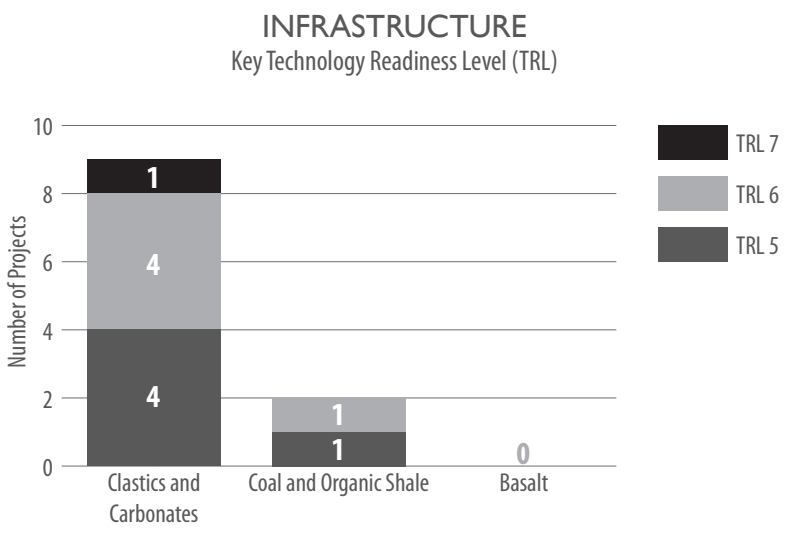


Figure 27. TRL Scores for Infrastructure Projects

Rating Summary

The critical technology challenges related to Infrastructure require a portfolio of technologies encompassing the three key technologies. For the FY14 assessment, the Basalt key technology did not include any active projects as defined in the TRL Methodology section. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the Infrastructure technology emerges as a range of TRL values. The overall readiness of the Infrastructure Technology Area is represented by the status of the individual projects evaluated in the portfolio, which have TRL scores ranging from 5 to 7.

Technology Readiness Level Range for Infrastructure

5–7

INFRASTRUCTURE

KEY TECHNOLOGIES

CLASTICS AND CARBONATES

Seven of the eleven potential storage reservoir classes are collectively referred to as clastics, and are derived primarily from sand deposited in a variety of depositional environments. These environments include river deltas and channels, ocean beaches and sand bars, offshore submarine fans, lakes, and desert dunes. The deposits formed in these different environments have distinct and unique internal architectures that control fluid flow within the reservoir.

9 PROJECTS
5–7 TRL RANGE

Two storage reservoir classes are referred to as carbonates, and are the product of both biological (e.g., coral reefs or oyster shell banks) and chemical depositional systems. Carbonate sediments formed in oceans are the result of tiny shells drifting down and accumulating as thick ooze on the seafloor. The ooze is transformed into rock over time. Water has reacted with carbonate rocks in some areas to create porosity and permeability, making these rocks of interest for CCS.

Nine projects within the Carbon Storage Infrastructure portfolio focused on assessing and validating clastic and carbonate reservoirs as a CCS technology option were assessed. The current TRL of this key technology spans a range of 5–7, consistent with the status of the individual technologies embedded within these projects.

COAL AND ORGANIC SHALE

Coals are deposited over a narrow range of depositional sedimentary environments, including swamps, marshes, and flood plains. Coal generally has lower permeability than clastic rock, but may offer opportunities for a very secure form of storage along with enhanced natural gas recovery. In coal, CO_2 will preferentially absorb to mineral surfaces, releasing methane, while permanently locking the CO_2 in place. Shale, deposited in a wide variety of depositional environments, is characterized by very fine-grained rock with low permeability. Shales form the confining layers for many clastic or carbonate reservoirs. However, some shales contain 1–2 percent organic material in the form of hydrocarbons, which provide an adsorption substrate for storage similar to coal.

Two projects within the Carbon Storage Infrastructure portfolio focused on assessing and validating coal/shale as a CCS technology option were assessed. The current TRL of this key technology spans the range of 5–6, consistent with the status of the individual technologies embedded within these projects.

2 PROJECTS
5–6 TRL RANGE

BASALT

Basalt is produced when magma exits and cools quickly outside of, or near, the Earth's surface. At the top of flows, hot gas bubbles are often trapped in quenched lava, forming a bubbly, vesicular texture having substantial porosity, offering the opportunity for CO_2 storage.

No projects under the Basalt key technology met the TRL assessment requirement (as explained on page 10); therefore zero projects were assessed in this key technology for the FY14 report. A small-scale injection (900 metric tons) was completed in FY13 and not included in the assessment. Additional projects may be performed in the future.

0 PROJECTS
N/A TRL RANGE

INFRASTRUCTURE

PORTFOLIO

Table 15. **Infrastructure Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Clastics and Carbonates			
Battelle Memorial Institute **FC26-05NT42589**	Midwest Regional Carbon Sequestration Partnership (MRCSP): Phases II and III	6	This injection project focuses on confirming that injection and storage can be achieved safely, permanently, and economically, and on supporting regulatory development and industry efforts to commercialize and deploy storage in the Midwest region. Specifically, this project-field validates technologies to prove adequate injectivity and available capacity, prove storage permanence, determine the areal extent of the CO_2 plume/pressure front, and assess risk at an industrial site in the Michigan Basin. Completion of the project will demonstrate the possibility for safe and permanent storage of CO_2 in the formations being studied.
Blackhorse Energy, LLC **FE0006823**	South Louisiana Enhanced Oil Recovery/Sequestration Demonstration Project	5	This project focuses on defining the regional opportunities for storage in carbonate and clastic depleted oil reservoirs and providing the foundation for larger volume projects in the Gulf Coast region. Field validation of emerging monitoring and site characterization technologies demonstrates the ability to permanently and efficiently store CO_2 in these formations. Specifically, this project is conducting CO_2 injection for EOR in the Wilcox sand formation Completion of this project will demonstrate safe and permanent storage of CO_2.
Montana State University **FC26-05NT42587**	Big Sky Regional Carbon Sequestration Partnership: Phase II and Phase III	5	This injection project focuses on confirming that injection and storage can be achieved safely, permanently, and economically, and on supporting regulatory development and industry efforts to commercialize and deploy storage in the Big Sky region. Specifically, this project field-validates technologies to prove adequate injectivity and available capacity, prove storage permanence, determine the areal extent of the CO_2 plume/pressure front, and assess risk. Completion of this project will demonstrate safe and permanent storage of CO_2.

Table 15. **Infrastructure Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
New Mexico Institute of Mining and Technology **FC26-05NT42591**	Southwest Regional Partnership on Carbon Sequestration: Phase II and Phase III	5	This injection project focuses on confirming that injection and storage can be achieved safely, permanently, and economically, and on supporting regulatory development and industry efforts to commercialize and deploy carbon storage in the Southwest region. Specifically, this project field-validates technologies to prove adequate injectivity and available capacity, prove storage permanence, determine the areal extent of the CO_2 plume/pressure front, and assess risk at an EOR site in the Texas Panhandle. Completion of this project will demonstrate safe and permanent storage of CO_2.
Southern States Energy Board **FC26-05NT42590.1**	SECARB Anthropogenic Injection: Phase III	6	This injection project focuses on providing information to help confirm that transportation, injection, and storage can be achieved safely, permanently, and economically, and on supporting regulatory development and industry in commercialization and deployment of storage in clastic saline formations in the Southeast region and Gulf Coast. In order to validate that storage can be conducted at commercial scale in these formations, field validation of technologies is being carried out to prove adequate injectivity and available capacity, prove storage permanence, determine the areal extent of the CO_2 plume/pressure front, and assess risk. Specifically, this project is carrying out CO_2 injection for saline storage in the Paluxy sandstone formation in the Citronelle field. Completion of this project will demonstrate safe and permanent storage of CO_2.
Southern States Energy Board **FC26-05NT42590.2**	SECARB Early Test Injection: Phase III	7	This injection project focuses on providing information to help confirm that transportation, injection, and storage can be achieved safely, permanently, and economically, and to help support regulatory development and industry in commercialization and deployment of storage in depleted oil reservoirs and clastic saline formations in the Gulf Coast region. In order to validate that storage can be conducted at commercial scale in these formations, field validation of technologies is being carried out to prove adequate injectivity and available capacity, prove storage permanence, determine the areal extent of the CO_2 plume/pressure front, and assess risk. Specifically, this project is carrying out CO_2 injection for EOR and saline storage in Tuscaloosa sandstone formation at the Cranfield site. Completion of this project will demonstrate safe and permanent storage of CO_2.
University of Illinois **FC26-05NT42588**	An Assessment of Geological Carbon Sequestration Options in the Illinois Basin: Phases II and III	6	This injection project focuses on confirming that transportation, injection, and storage can be achieved safely, permanently, and economically, and on supporting regulatory development and industry efforts to commercialize and deploy storage in the largest capacity saline reservoir in the Illinois Basin. Specifically, this project field validates technologies to prove adequate injectivity and available capacity, prove storage permanence, determine the areal extent of the CO_2 plume/pressure front, and assess risk. Completion of this project will demonstrate safe and permanent storage of CO_2.
University of Kansas Center for Research **FE0006821**	Small-Scale Field Test Demonstrating CO_2 Sequestration in Arbuckle Saline Aquifer and by CO_2-EOR at Wellington Field, Sumner County, Kansas	5	This project focuses on defining the regional opportunities for storage in carbonate and clastic saline formations and depleted oil reservoirs and providing the foundation for larger volume projects in the Mid-Continent region. Field validation of characterization, modeling, monitoring, validation, accounting, and assessment and risk management technologies demonstrates the ability to permanently and efficiently store CO_2 in these formations. Specifically, this project is conducting CO_2 injection for saline storage in the Arbuckle basal sandstone and dolomite and EOR storage in the overlying Mississippian siliceous dolomite oil reservoir at Wellington field. Completion of the project will demonstrate safe and permanent storage of CO_2.
University of North Dakota **FC26-05NT42592**	Plains CO_2 Reduction (PCOR) Partnership Phase II and Phase III	6	This injection project focuses on confirming that transportation, injection, and storage can be achieved safely, permanently, and economically, and on supporting regulatory development and industry efforts to commercialize and deploy storage in the Plains region. Specifically, this project provides field validation of adequate injectivity and proof of available capacity, storage permanence, the areal extent of the CO_2 plume/pressure front, and assessing risk through collaboration in an existing EOR operation. Completion of this project will demonstrate safe and permanent storage of CO_2.

Table 15. **Infrastructure Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Coal and Organic Shale			
CONSOL Energy, Inc. **FC26-01NT41148**	Enhanced Coalbed Methane Production and Sequestration of CO_2 in Unmineable Coal Seams	6	This injection project focuses on better defining the regional opportunities for the permanent storage of CO_2 in unmineable coal seams with the simultaneous enhancement of coalbed methane production. Injection limitations are examined by developing models and sensitivity analyses of the effect of reservoir parameters on methane production and CO_2 storage. The project provides the foundation for larger volume projects in the Appalachian region. Specifically, this project accomplishes its targets via field validation of emerging monitoring, verification, accounting, and assessment and site characterization technologies, which, in turn, demonstrates the ability to permanently and efficiently store CO_2 in these formations. Completion of the project will demonstrate safe and permanent storage of CO_2.
Virginia Polytechnic Institute and State University **FE0006827**	Central Appalachian Basin Unconventional (Coal/Organic Shale) Reservoir Small-Scale CO_2 Injection Test	5	This injection project focuses on better defining the regional opportunities for storage in coal and shale formations and provides the foundation for larger volume projects in the Appalachian region. Specifically, this project is performing an enhanced coalbed methane injection test where up to 20,000 tons of CO_2 will be injected into three legacy coalbed methane wells in Buchanan County, VA, and a huff-and-puff test in a Devonian shale gas well in Morgan County, TN, where 500 tons of CO_2 will be injected. Completion of the project will demonstrate safe and permanent storage of CO_2.

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CROSSCUTTING RESEARCH

The Crosscutting Research program is directed across four key technologies: **SENSORS AND CONTROLS** make available new classes of measurement tools that manage technology complexity; permit low-cost, robust process monitoring; and enable real-time optimization of fully integrated, highly efficient power-generation systems. Controls research centers around self-organizing information networks and distributed intelligence for process control and decision making. **SIMULATION-BASED ENGINEERING** includes an array computational techniques that represent the full range of energy science from reactive and multiphase flows up to a full-scale virtual and interactive power plant. Science-based models of the physical phenomenon occurring in fossil fuel conversion processes and development of multiscale, multiphysics simulation capabilities are just some of the tools and capabilities under this key technology. Also, risk analysis associated with carbon capture and storage is another facet of this key technology. **HIGH-PERFORMANCE MATERIALS** focuses on new materials that will lower the cost and improve the performance of fossil-based power-generation system components. Research focuses on development of computational tools to support predictive performance, failure mechanisms, and molecular design of materials. **ENVIRONMENT AND INNOVATIVE ENERGY CONCEPTS** encompasses the development of advanced emissions control technologies and coal utilization by-product research for existing plants, as well as Water-Energy Interface R&D encompassing the future impacts of water for advanced power systems and how R&D can address these pending issues. This key technology also supports the development of innovative cost-effective technologies that promote efficiency, environmental performance, availability of advanced energy systems, and the development of computational tools that shorten development timelines of advanced energy systems. This area provides for fundamental and applied research in innovative concepts with a 10–25-year horizon that offers the potential for technical breakthroughs and step-change improvements in power generation and the removal of environmental impacts from fossil energy-based power systems.

CROSSCUTTING RESEARCH

The Crosscutting Research program serves as a bridge between basic and applied research by fostering the development of innovative and transformational systems aimed at improving the efficiency and environmental performance and lowering the cost of today's fossil fueled energy conversion and storage technologies. The program's mission is to invest in advanced high-risk/high-reward innovative technologies that support the goals for the overall Clean Coal Research Program.

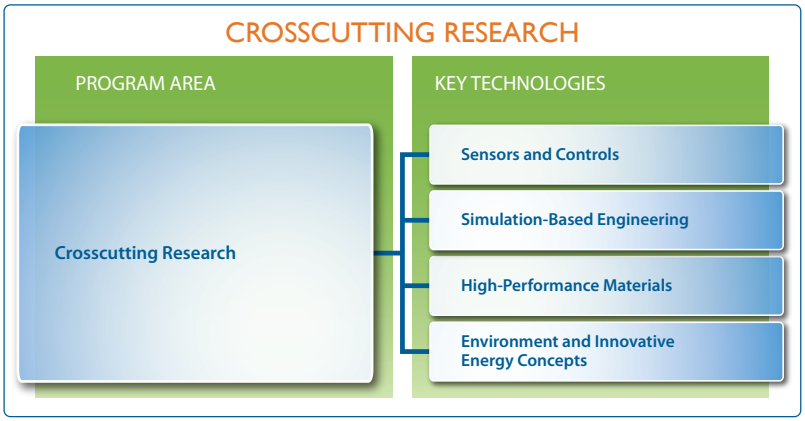

Figure 28. Crosscutting Research Key Technologies

Targets

The Crosscutting Research program supports the achievement of GPRA Endpoint Performance Target 2—*Advanced Energy Systems with CO_2 capture at no more than $40 per tonne of CO_2 captured by 2020.*

Benefits

The Crosscutting Research program develops a range of innovative and enabling technologies that are key to improving existing power systems and essential for accelerating the development of a new generation of highly efficient environmentally benign fossil fuel power systems. These key technologies are intended to offer viable step-change improvements in power system efficiency, reliability, costs, and environmental impacts. Sensors and Controls make available new classes of sensors and measurement tools that manage complexity, permit low-cost robust monitoring, and enable real-time optimization of fully integrated, highly efficient power-generation systems. Simulation-Based Engineering makes available integrated modeling tools with uncertainty quantification to provide a quantifiable predictive capability. High-Performance Materials research will significantly improve power plant performance and reduce the costs of existing and future fossil energy power-generation systems. Environment and Innovative Energy Concepts research assesses the potential advantages of these concepts.

Critical Challenges

The Crosscutting Research program bridges the gap between fundamental and applied R&D efforts. Specific challenges for each of the key technologies include:

Sensors and Controls

- Validating sensor data to provide confidence in data retrieved, especially when the advanced sensors are providing data that cannot be provided with existing technology.
- Providing technologies that transmit sensor data from harsh environments without direct connection to the control systems.
- Transforming laboratory research sensors to ruggedized devices that survive in the field for up to a year or more.

High-Performance Materials

- Developing long-term validation data on the critical properties associated with new materials to demonstrate their capabilities.
- Developing fabrication techniques that assure commercial manufacturing is capable of supplying the quantities of material with the quality characteristics of ones developed in the laboratory.

Simulation-Based Engineering

- Developing a practical framework to quantify the various types of uncertainties and assessing the impact of their propagation in the computer models of the physical system.
- Validating models so that the benefit of the integrated modeling tool is both consistent and complete.

Environment and Innovative Energy Concepts

- Developing validation data on the critical properties associated with a new technology to demonstrate its capabilities.

Projects Assessed

The TRLs of 116 projects were assessed in the Crosscutting Research program: 38 in Sensors and Controls, 22 in Simulation-Based Engineering, 54 in High-Performance Materials, and 2 in Environment and Innovative Energy Concepts. This collective body of work is being pursued to expand the state of knowledge and strengthen the technical basis for the ongoing and planned research in this area.

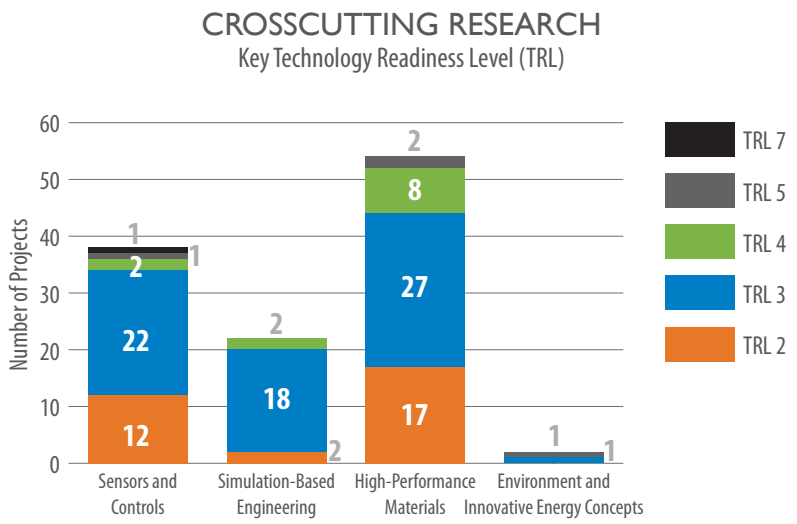

Figure 29. TRL Scores for Crosscutting Research Projects

Rating Summary

The critical technology challenges related to the Crosscutting Research program require a portfolio of technologies encompassing the four key technologies. The ongoing research associated with this body of work comprises a diverse collection of technologies, and the overall readiness of the Crosscutting technology emerges as a range of TRL values. The overall readiness of the Crosscutting Technology Areas is represented by the status of the 116 individual projects evaluated in the portfolio, which have TRL scores ranging from 2 to 7.

Technology Readiness Level Range for Crosscutting Research

2–7

CROSSCUTTING RESEARCH

KEY TECHNOLOGIES

SENSORS AND CONTROLS

The Sensors and Controls key technology makes available new classes of sensors and measurement tools that manage complexity, permit low-cost robust monitoring, and enable real-time optimization of fully integrated, highly efficient power-generation systems. Novel sensors and advanced process controls are critical and enabling technologies for advanced near-zero-emissions power systems. NETL's Crosscutting Research program is leading the effort to develop sensing and control technologies and methods to achieve seamless, integrated, and intelligent power systems.

38 PROJECTS
2–7 TRL RANGE

Harsh environments are inherent to new systems that aim to achieve high efficiency with low emissions. In addition, these systems are complex, with operational constraints and system integration challenges that push the limits of traditional process controls. As R&D enhances the understanding of these evolving advanced power-generation systems, it is clear that new, robust sensing approaches, including durable materials and highly automated process controls, are needed to optimize their operation and performance.

The Sensors and Controls key technology supports research to develop:

- A suite of high-temperature, harsh-environment sensors to measure temperature, pressure, and other process variables.
- Novel sensors to measure synthesis gas (e.g., hydrogen), flue gas constituents (e.g., nitrogen oxides), and trace contaminants (e.g., mercury).
- Low-cost distributed sensing concepts to support enhanced monitoring and control strategies.
- Advanced process control strategies for near-zero emissions in processes such as gasification and chemical looping.

Thirty-eight projects within the Crosscutting Research portfolio focused on improving sensor and control technologies were assessed. The current TRLs of this key technology range from 2–7 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

SIMULATION-BASED ENGINEERING

22 PROJECTS
2–4 TRL RANGE

The Simulation-Based Engineering key technology makes available integrated modeling tools with uncertainty quantification to provide a quantifiable predictive capability, ensuring that future design decisions—at ever increasing scale—lead to feasible design decisions to achieve optimal performance of advanced facilities, thus shortening lead time for technology development.

Simulation-Based Engineering combines technical knowledge, software development, computational power, data repository, experimental facilities, and unique partnerships to support research in providing timely and accurate solutions for complex power systems. Understanding the performance of complex flows and components used in advanced power systems and having the means to impact their design early in the developmental process provides significant advantages in product design. Computational models can be used to simulate the device and understand its performance before the design is finalized. Additionally, during new technology development—for example, the development of sorbent adsorber/desorber reactors for CO_2 capture—empirical scaleup information is not available because reactors at the required large scales have not been built. Traditional scaleup methods do not work well for many of the components that are present in complex power systems. Therefore, science-based models with quantified uncertainty are important tools for reducing the cost and time required for their development.

The Simulation-Based Engineering key technology supports research to develop:

- Computational physics-based models and tools to support the development and deployment of advanced fossil-fuel energy devices such as gasifiers and carbon capture reactors.
- Toolsets within the CCSI framework that incorporate commercial and open-source software currently in use by industry and new software tools as necessary to fill technology gaps.
- Risk analysis tools and improved science base generated by National Risk Assessment Partnership (NRAP) to aid operators in the design and application of monitoring and mitigation strategies for CO_2 storage.

Twenty-two projects within the Crosscutting Research portfolio focused on improving simulation-based engineering technologies were assessed. The current TRLs of this key technology range from 2–4 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

HIGH-PERFORMANCE MATERIALS

54 PROJECTS
2–5 TRL RANGE

High-Performance Materials research will significantly improve power plant performance and reduce the costs of existing and future fossil energy power-generation systems. This is accomplished through improved predictive modeling capabilities (for both structural characteristics and fundamental properties) that will optimize material design, reduce R&D costs, and expedite certification by agencies such as ASME and ASTM (American Society for Testing and Materials) so that these materials can be deployed with confidence by industry to shorten the time-to-market for meeting the technology's performance requirements.

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. To support these expectations, new materials are needed for these conditions and performance expectations.

The High-Performance Materials key technology supports research to develop:

- Computational materials modeling to enable rapid design and simulation of new and novel alloy materials with less repetitive testing. Computational design of materials has the potential to produce major breakthroughs.
- Superalloys and ferritic materials for use in advanced ultra-supercritical (A-USC) conditions of 760 °C and 350 bar pressure (≈5,000 pounds per square inch) to reduce costs, improve corrosion and erosion resistance, increase material strength, and reduce wall thickness.
- Functional materials for energy storage and high-performance materials with mechanical properties that can perform reliably at temperatures well over 1,000 °C.
- Advanced metallic and ceramic coatings, including nanomaterials, to provide thermal barrier protection for turbine blades, combustor components, and tubing.
- Validated computational models capable of simulating and predicting performance of materials in various types of power plants, including pressurized oxy-combustion, pressurized gasification, and CO_2 cycle plants.

Fifty-four projects within the Crosscutting Research portfolio focused on improving high-performance materials technology were assessed. The current TRLs of this key technology range from 2–5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

ENVIRONMENT AND INNOVATIVE ENERGY CONCEPTS

2 PROJECTS
3–5 TRL RANGE

Advanced power-generation concepts such as direct power extraction (DPE), 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. Although these innovative energy concepts (IECs) have significant potential advantages, practical development is stymied by uncertain component performance, the need for new materials, or simply the cost of development. The goal of the IEC is to utilize validated, computational simulations that can predict performance of these IECs to identify gaps in simulations and technology and guide development and accelerate the deployment of IEC technologies.

Environment and Innovative Energy Concepts research assesses the potential advantages of these concepts, determines their cost for practical development, identifies uncertainties related to component performance, determines the need for focused R&D, utilizes validated computational simulations that can predict performance of these concepts, identifies gaps in technology simulation tools and improves the toolset for this technology, and predicts the technologies' impact and reliance on supporting subsystems/processes.

The Environment and Innovative Energy Concepts key technology supports research to develop new breakthrough technologies that:

- Provide high efficiencies associated with transformational technology.
- Reduce CO_2 emissions without the energy penalties associated with current carbon capture processes.
- Reduce the need for water associated with power generation to conserve on this critical national resource.
- Identify sources of additional value from the use of coal as a fuel (e.g., recovering valuable byproducts from coal and/or coal ash).

Two projects within the Crosscutting Research portfolio focused on developing environment and innovative energy concepts were assessed. The current TRLs of these projects are 3 and 5 for the ongoing work, consistent with the status of the individual technologies embedded within these projects.

CROSSCUTTING RESEARCH

PORTFOLIO

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—Sensors and Controls			
Ames Laboratory **FWP-AL-06-205-020**	High-Density Sensor Network Development	3	This project will develop high-density sensor networking capability. The impact of this technology will be to lower operating costs by providing algorithms and synchronization strategies that will allow for improvement in control of combustion and gasification technologies especially able to respond to operational transients. Specifically, this project will work with sensor data and evaluate how processing and management of this data in a central strategy will allow synchronization of the output to allow better control of the facility.
Ames Laboratory **FWP-AL-12-470-009**	Merged Environment for Simulation and Analysis (MESA)	4	This project is focused on developing a MESA. The impact of this technology is to lower operating costs by facilitating advanced control strategies that use embedded intelligence at the sensor and component level to make faster decisions based on local information. Specifically, this project will develop a platform for investigating (1) advanced sensors with control strategies, (2) testing and development of sensor hardware, (3) various modeling in the loop algorithms, and (4) other advanced computational algorithms for improved plant performance using sensors, real-time models, and complex systems tools.
General Electric Company **FE0010116**	Multipoint Pressure and Temperature Sensing Fiber-Optic Cable for Monitoring CO_2 Sequestration	3	This project will focus on development of a rugged, low-cost CO_2 sensor capable of monitoring CO_2 leakage under the harsh environment of a deep injection well. Improved knowledge of sensors will promote safe operation of sequestration in geologic strata. Specifically, this project will test prototypes at moderate depths of up to 100 meters and if successful, subsequent development is planned to enable operation at depths of a mile with pressures up to 2,000 psi.
Intelligent Optical Systems, Inc. **FE0010318**	Intrinsic Fiber-Optic Chemical Sensors for Subsurface Detection of Carbon Dioxide	4	The project will demonstrate fiber-optic sensor prototypes for gas-phase and/or dissolved CO_2 monitoring capable of withstanding corrosive liquids and elevated temperatures. The impact of this technology is to lower operating costs by providing improved monitoring devices used to measure and verify the integrity of CO_2 sequestration sites. Specifically, this project will design a field-ready sensor based on an intrinsic fiber-optic system for subsurface CO_2 plume migration monitoring and above-zone leak detection.
Missouri University of Science and Technology **FE0001127**	Microstructured Sapphire Fiber Sensors for Simultaneous Measurements of High Temperature and Dynamic Gas Pressure in Harsh Environments	3	This project will develop advanced temperature-measuring sensor devices. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this sensor utilizes a sapphire-based fiber and a sapphire wafer to form a point sensor to measure temperature and pressure data from inside a gasifier or burner at temperatures up to 1,600 °C.
Missouri University of Science and Technology **FE0009843**	Robust Ceramic Coaxial Cable Downhole Sensors for Long-Term In Situ Monitoring of Geologic CO_2 Injection	2	This project will develop sensors for in situ downhole monitoring of geologic CO_2 injection and storage. The impact of this technology is to lower operating costs by providing improved monitoring devices used to measure and verify the integrity of CO_2 sequestration sites. Specifically, this project will develop a robust ceramic coaxial cable sensor platform with high spatial and temporal resolutions based on a recent invention of coaxial cable Bragg gratings and coaxial cable Fabry-Pérot interferometers in conjunction with the latest available high-temperature, ultralow-loss ceramic coaxial cables.
NETL-ORD **FWP-2012.04.01.2**	Innovative Process Technologies—Task 2: Optical Sensors Research and Development	3	This project will improve fiber-optic and optical waveguide materials. This impact of this technology is to lower operating costs by supporting efforts to develop sensors for harsh conditions to assist in monitoring the operation and performance of critical components within gasification facilities. Specifically, this project will test portable Raman sensors in operation at onsite and offsite facilities.
New Mexico Institute of Mining and Technology **FE0009878**	Development of a CO_2 Chemical Sensor for Downhole CO_2 Monitoring in Carbon Sequestration	3	This project focuses on development of a CO_2 chemical sensor that can be used to monitor leakage of CO_2 into a sequestration monitoring well. The impact of this technology is to lower costs by providing improved monitoring devices used to measure and verify the integrity of CO_2 sequestration sites leading to development of a robust pH sensor for in situ monitoring of subsurface waters. Specifically, this project will test a newly designed pH electrode that can resist the high pressures, temperatures, and salinity in a monitoring well and will measure the water such that it will reflect dissolved CO_2 and can thus infer CO_2 plume migration.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Oregon State University **FE0011403**	Intelligent Coordination of Heterogeneous Sensors in Advanced Power Systems	2	This project will provide intelligent coordination of heterogeneous sensors in advanced power systems. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will provide sensor deployment, coordination, and networking algorithms for large numbers of sensors to ensure the safe, reliable, and robust operation of advanced energy systems deriving sensor performance metrics for heterogeneous sensor networks and demonstrating effectiveness, scalability, and reconfigurability of heterogeneous sensor networks in advanced power systems.
Oregon State University **FE0012302**	Evolving Robust and Reconfigurable Multi-Objective Controllers for Advanced Power Systems	2	This project will focus on deriving, implementing, and testing bio-mimetic control and multi-objective optimization algorithms that promote robust and reconfigurable performance in an advanced power system. Implementation of these control algorithms will promote the long-term objective of providing a comprehensive solution multi-objective control of advanced power systems where no detailed system model is required for real-time control that will reduce operating costs. Specifically, this project will enable development of reconfigurable multi-objective controllers for power systems control.
Palo Alto Research Center Incorporated **FE0013062**	Heat-Sensor Harsh-Environment-Adaptable Thermionic Sensor	2	This project will develop and demonstrate a thermionic element wireless temperature and pressure sensor. The technology will lower operating costs by supporting efforts to develop a high-temperature wireless component-monitoring sensor to assist in reducing forced outages 5–10 percent in critical components at operating power plants. Specifically, this project will integrate thermionic elements into a functional package with the capability to measure additional strain, flux, and flow rate process parameters, as well as incorporate a completely wireless configuration.
Sandia National Laboratories **FWP-10-014451**	Laser-Based Detection of Trace Level Contaminants	3	This project will develop an instrument for high-sensitivity, real-time detection of elemental selenium (Se) and selenium dioxide (SeO_2). The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a boiler to better control its operation. Specifically, this project will employ laser-induced fluorescence (LIF) detection schemes selective for the species of interest, thereby enabling in situ monitoring of selenium compounds in flue gas.
Stanford University **FE0001180**	Tunable Diode Laser Sensors to Monitor Temperature and Gas Composition in High-Temperature Coal Gasifiers	5	This project will develop advanced gas measurement sensor devices. The impact of this technology will lower operating costs by allowing more accurate measurement of the conditions inside the harsh environment of gasifiers to better control their operation. Specifically, this sensor utilizes a tunable diode laser to measure H_2O, carbon monoxide, CO_2, and CH_4 concentrations inside a high-temperature, high-pressure vessel.
Texas Tech University System **FE0005749**	Model-Based Sensor Placement for Component Condition Monitoring and Fault Diagnosis in Fossil Energy	3	This project will focus on development of algorithms that will improve the operation and performance of advanced power-generating systems. Improvements in power industry algorithms will improve power plant operation resulting in greater efficiency, improved grid dispatch, and lower emissions that will reduce operating costs. Specifically, this project will use dynamic simulation to evaluate optimum sensor placement to detect plant conditions and predict equipment degradation thereby contributing to optimal operation under transient conditions and facilitating maintenance planning.
The Research Foundation of State University of New York **FE0007190**	Heat-Activated Plasmonics-Based Harsh-Environment Chemical Sensors	3	This project will develop heat-activated plasmonics-based harsh-environment chemical sensors. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will develop a suite of plasmonic-based gas sensors capable of operating in 500–900 °C mixed gas environments. The approach is based on optical interrogation of electron-beam-patterned gold nanoparticles embedded within metal oxide nanocomposites.
United Technologies Corporation **FE0012299**	Additive Topology Optimized Manufacturing with Embedded Sensing	2	This project will develop a suite of sensors into an industrial gas turbine airfoil. The impact of this technology is to lower operating costs by supporting improvements to the next generation of combustion turbines' operation and performance. Specifically, this project will integrate the smart parts developed by DOE's projects for remotely powered and sensed, and provide real-time diagnostics when coupled to a health-utilization-monitoring system.
University of Central Florida **FE0007004**	Wireless, Passive Ceramic Strain Sensors for Turbine Engine Applications	3	This project will develop wireless passive ceramic strain sensors for turbine engine applications. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will develop an accurate and robust wireless passive high-temperature sensor for in situ measurement of strains inside turbine engines in coal-based power systems.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
University of Connecticut **FE0011577**	Metal Oxide/Nitride Heterostructured Nanowire Arrays for Ultra-Sensitive and Selective Multimode High-Temperature Gas Detection	2	This project will develop and test new sensor materials for harsh environments experienced in fossil energy systems. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will develop metal oxide/nitride heterostructured nanowire arrays for ultra-sensitive and selective multimode high-temperature gas detection sensors.
University of Florida **FE0012370**	High-Temperature Sapphire Pressure Sensors for Harsh Environments	2	This project will demonstrate advanced manufacturing technologies for high-temperature pressure sensors. The impact of this technology is to lower operating costs by supporting efforts to develop sensors for harsh conditions to assist in monitoring the operation and performance of critical components in power plants, combustion turbines, and gasification facilities. Specifically, this project will identify laser ablation process variables supporting the development of cost/energy-efficient procedures for rapid joining of sensor components resulting in fully packaged sapphire optical sensors capable of deployment in gas turbine applications at temperatures in excess of 1,000 °C and pressures up to 1,000 psi.
University of Illinois **FE0011227**	Multi-Objective Optimal Sensor Deployment Under Uncertainty for Advanced Power Systems	2	This project will develop a multi-objective optimal sensor for deployment under uncertainty in advanced power systems. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will develop a CAPE-OPEN compliant virtual sensing capability and multi-objective stochastic programming capability for optimal sensor placement under uncertainty for advanced power systems with various objectives like efficiency, maximum information, and cost.
University of Maine **FE0007379**	High-Temperature Wireless Sensor for Harsh-Environment Condition Monitoring	3	This project will develop and demonstrate the performance of wireless microwave acoustic sensors for temperature and pressure measurement in high-temperature environments. The impact of this technology is to reduce operating costs by supporting efforts to develop a high-temperature wireless component-monitoring sensor to assist in reducing forced outages 5–10 percent in critical components at operating power plants. Specifically, this project will develop small battery-free surface acoustic wave sensors with integrated antennas composed of novel materials for real-time monitoring in conditions up to 1,200 °C and 750 psi.
University of Missouri System **FE0012272**	Additive Manufacture of Smart Parts with Embedded Sensors for In Situ Monitoring in Advanced Energy Systems	2	This project will develop a suite of sensors into an industrial gas turbine airfoil. The impact of this technology is to lower operating costs by supporting development of improvements for next-generation combustion turbine operation and performance. Specifically, this project will produce a smart part that will maintain its structural integrity, be remotely powered and sensed, and provide real-time diagnostics when coupled to a health-utilization-monitoring system.
University of Pittsburgh **FE0003859**	Development of Metal-Oxide Nanostructure-Based Optical Sensors for Fossil-Fuel-Derived-Gas Measurement at High Temperature	3	This project will develop metal-oxide nanostructure-based optical sensors for fossil-fuel-derived-gas measurement at high temperatures. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will use a laser nanofabrication technique to produce 3-D structurally functional metal-oxide nanomaterials for high-temperature gas sensing to be integrated on two distinct optical-sensor platforms.
University of Texas at El Paso **FE0007225**	Gallium Oxide Nanostructures for High-Temperature Sensors	3	This project will design gallium oxide (Ga_2O_3)-based nanostructured materials capable of operating under extreme conditions. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will develop high-temperature O_2 sensors based on pure and doped Ga_2O_3 nanostructures, capable of operating at high temperature in harsh conditions by (1) fabricating high-quality pure and doped Ga_2O_3-based materials, (2) optimizing conditions to produce unique architectures and morphology at the nanoscale, and (3) deriving the structure-property relationships at nanoscale dimensions and demonstrating oxygen-sensor stability.
University of Texas at El Paso **FE0011235**	Investigation on Pyroelectric Ceramic Temperature Sensors for Energy System Applications	3	This project will develop a self-powered, low-cost wireless temperature sensor capable of withstanding harsh environments. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will fabricate and characterize pyroelectric ceramic temperature-sensor materials that will be used to construct a wireless sensing system capable of operating at high temperatures and under harsh conditions.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
University of Texas at El Paso **FE0012321**	Investigation of Smart Parts with Embedded Sensors for Energy System Applications	3	This project will optimize advanced 3-D manufacturing processes for embedded sensors in energy system components. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will (1) fabricate energy-system-related components with embedded sensors, (2) evaluate the mechanical properties and sensing functionalities of the smart parts with embedded piezo-ceramic sensors, and (3) assess the in situ sensing capability of energy system parts.
University of Texas at El Paso **NT0008022**	Investigation of WO_3-Based H_2S Sensor Materials for Coal Gasification Systems	3	This project will investigate a tungsten trioxide (WO_3)-based H_2S sensor material for coal gasification systems. The impact of this technology is to lower operating costs by supporting efforts to develop sensors for harsh conditions to assist in monitoring the operation and performance of critical components within gasification facilities. Specifically, this project will use a comprehensive suite of measurements, together with temperature-dependent electrical characterizations and performance evaluation tests, to assess the feasibility of titanium-, gold-, and aluminum-doped WO_3 materials for detecting and monitoring H_2S in syngas.
University of Utah **FE0006947**	In Situ Acoustic Measurements of Temperature Profile in Extreme Environments	3	This project will develop in situ acoustic measurements of temperature profiles in extreme environments. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will develop and validate methods for noninvasive ultrasound measurements of temperature distribution inside refractories during coal gasification and for measuring refractory thickness in terms of their accuracy, response time, and robustness.
Virginia Polytechnic Institute and State University **FC26-05NT42441**	Novel Modified Optical Fibers for High-Temperature In Situ Miniaturized Gas Sensors in Advanced Fossil Energy Systems	3	This project is developing novel modified fiber materials for high-temperature gas sensors. This impact of this project will be to more accurately measure the conditions within a boiler or gasifier to better control the operation of the facility in a dynamic fashion and therefore lower operating costs. Specifically, this project will use evanescent wave absorption in standing-hole optical fibers to improve response time limitations of currently available holes.
Virginia Polytechnic Institute and State University **FC26-99FT40685**	Single-Crystal Sapphire Optical Fiber Sensor Instrumentation	7	This project will develop a sapphire-based sensor that records temperature data at up to 1,600 °C. The impact of this technology is to lower operating costs by supporting efforts to develop sensors for harsh conditions to assist in monitoring the operation and performance of critical components within gasification facilities. Specifically, this project utilizes a sapphire-based fiber and a sapphire wafer to form a point sensor that is referred to as an extrinsic Fabry-Pérot interferometric sensor.
Virginia Polytechnic Institute and State University **FE0005703**	Distributed Fiber-Optic Sensor for Online Monitoring of Coal Gasifier Refractory Health	3	This project will develop a high-temperature distributed sensing platform for monitoring a gasifier's refractory wall. The impact of this technology is to lower operating costs by helping to reduce forced outages by 5–10 percent for power-generation systems. Specifically, this project will be placing the photonic crystal fiber sensor at the back side of the innermost gasifier liner.
Virginia Polytechnic Institute and State University **FE0007405**	Embedded Active Fiber-Optic Sensing Network for Structural Health Monitoring in Harsh Environments	3	This project will develop an embedded, remotely controlled/monitored quasi-distributed sensing network for nondestructive evaluation (NDE) of advanced fossil power systems. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will develop simultaneous multi-parameter measurement techniques (temperature, strain, corrosion, cracks) that use a fiber-optic NDE sensing system and will evaluate the technology in a laboratory test apparatus.
Virginia Polytechnic Institute and State University **FE0012274**	Reduced Mode Sapphire Optical Fiber and Sensing System	2	This project will develop real-time, accurate and reliable monitoring of temperatures at distributed locations of sensors for harsh conditions. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will design a sapphire fiber waveguide that will take advantage of the high-temperature stability and corrosion resistance of sapphire and use a novel and precise etching technique that will significantly reduce (>50 percent) the mode volume in a sapphire fiber.
West Virginia University Research Corporation **FE0003872**	High-Temperature Nano-Derived Micro-H_2 and H_2S Sensors	3	This project will develop microscale chemical sensors and sensor arrays to detect gases such as H_2 and H_2S within high-temperature environments. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will demonstrate an innovative microcasting process for forming chemiresistive sensors with 20–100 micrometer feature size of various geometries composed of nanocomposite electrodes that display high-temperature microstructural and morphological stability.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
West Virginia University Research Corporation **FE0005717**	Development of Self-Powered, Wireless-Ready, High-Temperature Electrochemical Sensors of In Situ Corrosion	3	This project will develop in situ sensors for corrosion monitoring systems. The impact of this technology will be to lower operating costs by better prediction of maintenance requirements for combustion and gasification systems to improve availability of power-generation components. Specifically, this project will experiment with an assortment of materials suitable for fabrication of sensor electrodes.
West Virginia University Research Corporation **FE0011300**	Graphene-Based Composite Sensors for Energy Applications	3	This project will develop gas sensors for harsh-environment applications with high sensitivity, selectivity, and rapid response times. The impact of this technology will be to lower operating costs by allowing more accurate measurement of the conditions inside a gasifier or boiler to better control their operation. Specifically, this project will develop graphene-based composites that enable gas sensors to be fabricated for high-temperature (up to 1,000 °C) applications.
West Virginia University Research Corporation **FE0012383**	Smart Refractory Sensor Systems for Wireless Monitoring of Temperature, Health, and Degradation of Slagging Gasifiers	2	This project will demonstrate a high-temperature sensor concept for the monitoring of reaction conditions within slagging coal gasifiers. This impact of this technology is to lower operating costs by supporting efforts to develop sensors for harsh conditions to assist in monitoring the operation and performance of critical components within gasification facilities. Specifically, this project will (1) develop a smart refractory brick, which will contain embedded temperature, strain/stress, and spallation sensors and (2) develop a method to interconnect the sensors to the reactor exterior.
West Virginia University Research Corporation **FE0012451**	Development of Integrated Biomimetic Framework with Intelligent Monitoring, Cognition, and Decision Capabilities for Control of Advanced Energy Plants	2	This project will develop algorithms and methodologies for designing control systems. The impact of this technology is to lower operating costs by supporting efforts to develop distributed intelligence for optimal control of advanced energy plants. Specifically, the project will use biomimetics to develop algorithms applicable to other process and power plants for which plant models are available.
Key Technology—Simulation-Based Engineering			
Ames Laboratory **FWP-AL-07-450-004**	Virtual Advanced Power Training Environments	4	This purpose of this project is to develop a set of advanced power training environments for a virtual power plant and an IGCC simulator. The impact of this project will be to provide a training environment to allow operators of advanced power-generation facilities to gain an improved understanding of the plant before stepping foot in a real plant, which will reduce operating costs. Specifically, this project will bring together existing NETL capabilities to create an integrated training and research environment by developing new dynamic simulations of these advanced power-generation facilities.
Florida International University **FE0007260**	Development of a Two-Fluid Drag Law for Clustered Particles Using Direct Numerical Simulation and Validation Through Experiments	3	This project will focus on the development of an accurate drag correlation for gas-solid multiphase flow that includes the effect of clustered particles. Improvements in numerical computation techniques for the flow of solids in gases will lead to improvement in the design of advanced next-generation power-generation equipment and will result in lower capital costs. Specifically, this project will lead to more accurate closure laws needed to capture the interaction of gas and solid phases in CFD simulation of multiphase reactors such as a coal gasifiers and fluidized-bed boilers.
Illinois Institute of Technology **FE0003997**	Computational Fluid Dynamic Simulations of a Regenerative Process for Carbon Dioxide Capture in Advanced Gasification-Based Power Systems	2	This project will develop a CFD simulation of a regenerative process for CO_2 capture in advanced gasification-based systems. Improvements in numerical computation techniques for the flow of solids in gases will lead to improvement in the design of advanced next-generation power-generation equipment resulting in lower capital and operating costs. Specifically, this project will develop a CFD model to perform simulations to describe the heterogeneous gas-solid absorption/regeneration and water-gas-shift reactions in the context of a multiphase regenerative magnesium oxide-based process for simultaneous removal of CO_2 and enhancement of H_2 production in coal gasification processes.
Iowa State University **FE0006946**	Multiphase Flow Research-Uncertainty Quantification Tools for Multiphase Gas-Solid Flow Simulations Using MFiX [Multiphase Flow with Interphase eXchanges]	3	This project has developed polynomial chaos methods to evaluate the polynomial chaos modes from the outputs of an existing numerical implementation of the model (the nonintrusive approach). This project will develop and implement an efficient nonintrusive UQ method for gas-solids flow simulations, allowing for error estimation and sampling requirements for UQ analysis that will reduce capital costs. Specifically, this project will contribute to the design and deployment of more efficient and environmentally benign power-generation systems by reducing the amount of uncertainty that must currently be factored into the design of coal-fired power-generation equipment and systems, thus reducing design uncertainty factors resulting in lower equipment and operating costs.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
NETL-ORD **FWP-2012.04.01.6**	Innovative Process Technologies—Task 6: Multiphase Flow	3	The purpose of this project is to make suitable modification to MFiX code structure as and where needed to increase performance. The impact of this project is to reduce design time for gasification and combustion systems and supporting systems which will result in lower capital costs for future facilities. Specifically, this project will identify the terms that need to be modeled within the large particle simulation framework and formulate models for each term in dynamic equations.
NETL-ORD **FWP-2012.04.02.2**	Carbon Capture Simulation Initiative—Task 2: Basic Data Submodels and UQ	3	This project will develop and apply a system-level methodology to support site-specific risk evaluations for the risk analysis and decision making framework. The impact of this project is to provide tools that will reduce the time to engineer and design advanced clean coal technologies and sequestration sites that will lower capital and operating costs. Specifically, this project will integrate assessment models consisting of reduced-order models based on detailed physical and chemical models with laboratory and field data.
NETL-ORD **FWP-2012.04.02.3**	Carbon Capture Simulation Initiative—Task 3: High-Resolution Filtered Submodels	3	This project will develop the science base to quantify risk profiles associated with geologic carbon storage sites. The impact of this project is to provide tools that will reduce the time to engineer and design advanced clean coal technologies and sequestration sites that will lower capital and operating costs. Specifically, this project will develop detailed particle models to support more detailed and accurate device-scale modeling.
NETL-ORD **FWP-2012.04.02.4**	Carbon Capture Simulation Initiative—Task 4: Validated High-Fidelity CFD Models and UQ	3	This project will develop and validate a set of device-scale CFD models. The impact of this project is to provide tools that will reduce the time to engineer and design advanced clean coal technologies and sequestration sites that will lower capital and operating costs. Specifically, this project focuses on validation of the models using various sources of experimental data.
NETL-ORD **FWP-2012.04.02.5**	Carbon Capture Simulation Initiative—Task 5: Process Models	3	This project will develop risk-based monitoring and mitigation strategies/protocols to provide insight into the most effective approaches to lower uncertainties and risk for the risk analysis and decision making framework. The impact of this project is to provide tools that will reduce the time to engineer and design advanced clean coal technologies and sequestration sites that will lower capital and operating costs. Specifically, this project will complete the development and validation of a set of process models for the design and analysis of solid sorbent carbon capture processes.
NETL-ORD **FWP-2012.04.02.6**	Carbon Capture Simulation Initiative—Task 6: Process Optimization and UQ	3	This project will focus on the continued development and integration of the ALAMO code (Automated Learning of Algebraic Models for Optimization). The impact of this project is to provide tools that will reduce the time to engineer and design advanced clean coal technologies and sequestration sites that will lower capital and operating costs. Specifically, this project allows detailed process optimization using rigorous, derivative-based optimization codes enabling the optimization algorithms to determine optimal process configurations.
NETL-ORD **FWP-2012.04.02.7**	Carbon Capture Simulation Initiative—Task 7: Integrated Framework for Dynamics and Control	3	This project will develop and demonstrate tools for developing dynamic reduced models from rigorous dynamic process simulations. The impact of this project is to provide tools that will reduce the time to engineer and design advanced clean coal technologies and sequestration sites that will lower capital and operating costs. Specifically, this project enables faster computation of system responses, allowing an advanced process control framework and the integration of the dynamic models within a larger dynamic simulation.
NETL-ORD **FWP-2012.04.02.8**	Carbon Capture Simulation Initiative—Task 8: Risk Analysis and Decision Making	3	This project will develop an expert elicitation system to assess TRLs. The impact of this project is to provide tools that will reduce the time to engineer and design advanced clean coal technologies and sequestration sites that will lower capital and operating costs. Specifically, this project estimates the level of uncertainty for the simulations and determines exit criteria from each TRL. This includes risk factor analysis to identify steps having the greatest impact on risk (schedule, cost, etc.) and links to the stage-gate process.
NETL-ORD **FWP-2012.04.02.9**	Carbon Capture Simulation Initiative—Task 9: Crosscutting Integration Tools	3	This project will develop a data management system. The impact of this project is to provide tools that will reduce the time to engineer and design advanced clean coal technologies and sequestration sites that will lower capital and operating costs. Specifically, this project will develop a data management system to manage data models, knowledge interchange, and model results including data progeny.
NETL-ORD **FWP-2012.04.03.2**	National Risk Assessment Program—Task 2: Develop a Methodology for Quantification of Site-Specific Risk Profiles	3	The purpose of this project is to develop a methodology for quantification of site-specific risk profiles. The impact of this project is to ensure sequestration projects proceed with minimal risk which will lower their operating costs. Specifically, this project will develop third-generation risk profiles building upon past work.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
NETL-ORD **FWP-2012.04.03.3**	National Risk Assessment Program—Task 3: Ensure the Science Base and Validity of Methodology from Quantifying Site-Specific Risk Profiles	3	The purpose of this activity is to ensure the science base and validity of the methodology for quantifying site-specific risk profiles. The impact of this project is to ensure sequestration projects proceed with minimal risk, which will lower their operating costs. Specifically, this project will (1) assess gaps and needs of the technology, (2) quantify predicted release through reservoir seals, (3) complete wellbore models for long-term effects, and (4) improve quantification of predicted response to groundwater systems due to CO_2 and brine leakage.
NETL-ORD **FWP-2012.04.03.5**	National Risk Assessment Program—Task 5: Develop Monitoring and Mitigation Strategies that Lower Uncertainties and Risk	3	The purpose of this activity is to develop monitoring and mitigation strategies to lower uncertainties and risk. The impact of this project is to ensure sequestration projects proceed with minimal risk, which will lower their operating costs. Specifically, this project will develop risk monitoring strategies.
Princeton University **FE0006932**	Implementation and Refinement of a Comprehensive Model for Dense Granular Flows	3	This project will focus on using a combination of continuum simulations for model validation and discrete particle simulations for model refinement. The project will develop models to more accurately predict dense granular flows, which are an integral part of the design in both power-generation and industrial processes. Specifically, this project will connect macroscopic and microscopic descriptions of the flow, allowing for the construction of a more detailed model for the particle-phase stress, and the refinement will be implemented into MFiX and validated by simulating various tests.
Sandia National Laboratories **FWP-FEW0709**	Coal Combustion and Gasification Science	3	This project will focus on the development of key fundamental information: the kinetics of advanced combustion and gasification systems to assist with design and commercialization. Improvement in this basic engineering data will improve the understanding of the formation and destruction of NO_x during O_2/CO_2 recycle combustion of PC for zero-emission power, which is important for oxygen-enhanced coal combustion. Specifically, this project will provide experimental measurements of the gasification kinetics of coal char at high temperatures and elevated pressures, which are needed to improve the phenomenological understanding and comprehensive CFD modeling of entrained flow gasifiers (e.g., Shell, E-GAS, and GE designs) and transported-bed gasifiers (Transport Reactor Integrated Gasification [TRIG™] design).
Tuskegee University **FE0007520**	Study of Particle Rotation Effect in Gas-Solid Flows Using Direct Numerical Simulation with a Lattice Boltzmann Method	3	This project will focus on using the DNS method to investigate the drag force between solid particles and gas phases. Improvements in numerical computation techniques for the flow of solids in gases will lead to the improvement in design of advanced next-generation power-generation equipment. Improvements in numerical computation techniques for the flow of solids in gases will lead to the improvement in design of advanced next-generation power-generation equipment resulting in lower capital and operating costs. Specifically, the project will use particle rotation effects in gas-solid flows using DNS with a Lattice Boltzmann method accurately representing particle shapes during simulation and will use experimental results obtained using high-speed particle-imaging methods to validate the model.
University of California, Merced **FE0003801**	High-Fidelity Multiphase Radiation Module for Modern Coal Combustion Systems	4	This project will focus on development of optimal radiation tools to allow efficient high-fidelity determination of radiative fluxes and sources in real-time in two-phase coal combustion systems. Improvements in power industry algorithms will promote high-accuracy simulations to improve power plant design and operation resulting in greater efficiency, improved grid dispatch, and reduced emissions. Specifically, this project will provide a means to describe solid particles (coal, ash, soot, bed material) using state-of-the-art two-phase spectral models that will be integrated into MFiX.
University of Colorado **FE0007450**	Quantifying the Uncertainty of Kinetic-Theory Predictions of Clustering	3	This project will focus on implementing and validating a new granular stress model in MFiX. The project will develop models to more accurately predict dense granular flows, which are an integral part of the design in both power-generation and industrial processes. Specifically, this project will determine the relative importance of the driving forces for instabilities in high-velocity gas-solid flows, and will establish the suitability first-principles theory, with no adjustable parameters, to accurately predict the type, onset, evolution, and steady-state characteristics of such instabilities, leading to modifications for MFiX implementation and validation tests.
University of Texas at San Antonio **FE0011453**	Use of an Accurate DNS Method to Derive, Validatem and Supply Constitutive Equations for the MFiX Code	2	This project will focus on deriving, validating, and supplying constitutive equations for the MFiX code. This project will develop models to more accurately predict flows, which are an integral part of the design in both power-generation and industrial processes. Specifically, this project will improve the model to capture more complex flow behavior by using a steady shear rheological model, performing MFiX simulations of various test problems, examining the effect conditions on flow, and modifying MFiX implementation and conducting validation tests.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Key Technology—High-Performance Materials			
Ames Laboratory **FWP-AL-07-360-019**	Computational and Experimental Development of Novel High-Temperature Alloys	3	This project will develop high-temperature, oxidation-resistant alloys capable of meeting the requirements of high-temperature gas turbine components. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will investigate a 20 percent molybdenum (Mo)-balanced nickel aluminum (NiAl) alloy that has promising characteristics with respect to high-temperature oxidation resistance.
Ames Laboratory **FWP-AL-10-450-007**	Design of Multiscale Systems	3	This project will focus on the design of multiscale materials for application in advanced power plants. Implementation of these algorithms will promote the strategies and informational framework needed to design new materials suitable for operation in the harsh environment of advanced power systems, which will result in lower operating costs for these facilities. Specifically, this project will be conducted in an integrated manner across length and time scales, creating the ability to design and tailor material properties for specific applications.
Ames Laboratory **FWP-AL-99-501-032**	Improved Atomization Processing for Fossil Energy Applications	3	This project will improve the design of high-efficiency gas atomization nozzles in order to control particle size distribution and maximize the yield of powder in special size classes most suitable for high-strength structural applications made by net-shape or near net-shape processing (i.e., additive manufacturing) and for thermal spray coatings. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will conduct powder production in advanced laboratory atomization systems to demonstrate steady-state operation, and will develop control systems suitable for industrial use.
Argonne National Laboratory **FWP-49640**	Materials Research for Coal Conversion and Utilization Processes	4	This project will evaluate corrosion and mechanical properties of materials in combustion and mixed-gas environments. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will identify suitable materials with adequate mechanical properties to solve issues with high-temperature service and reduce ASME code approval time by conducting experiments to establish the corrosion behavior of materials developed for the oxy-fuel environment.
Auburn University **FE0011245**	Reduced-Cost Bond Layers for Multilayer Thermal/ Environmental Barrier Coatings	2	This project will develop reduced-cost bond layers for multilayer TBCs/environmental barrier coatings (EBCs). Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will develop a TBC/EBC coating system and investigate the degradation of the coating system, focusing on the interlayer between the alloy and ceramics TBC and the hot corrosion behavior in different gas atmospheres.
Babcock & Wilcox Power Generation Group, Inc. **FC26-07NT43097**	Development of Computational Capabilities to Predict the Corrosion Wastage of Boiler Tubes in Advanced Combustion Systems	3	This project will develop computational models to predict corrosion associated with staged combustion techniques used to reduce NO_x emissions. The project will facilitate capital cost improvements in boiler design tailored to withstand the locally corrosive environments associated with staged combustion resulting in lower operating costs. Specifically, this project will develop advanced modeling techniques to predict areas of corrosion within a boiler and will conduct tests to validate these models.
Brown University in Providence in State of RI **FE0008933**	Advanced Thermal Barrier Coatings for Next-Generation Gas Turbine Engines Fueled by Coal-Derived Syngas	2	This project will develop advanced TBCs for next-generation gas turbine engines fueled by coal-derived syngas. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will develop porous TBC ceramics/CMAS [calcium-magnesium aluminosilicate] interactions using model studies that will lead to fabrication and testing to understand mitigation mechanisms.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Carnegie Mellon University **FE0003840**	High-Resolution Modeling of Materials for High-Temperature Service	3	This project will develop high-resolution modeling of materials for high-temperature service. Improvements to high-temperature advanced-materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will develop high-resolution methods for modeling the 3-D mechanical response of metallic alloys when exposed to high temperatures by simulating plastic deformation and damage accumulation of polycrystalline materials at the grain scale.
Case Western Reserve University **FE0007270**	An Information Theoretic Framework and Self-Organizing Agent-Based Sensor Network Architecture for Power Plant Condition Monitor	2	This project will focus on development of algorithms that will better enable advanced power-generation systems to respond to the challenges of electric generation requirements in the future. Improvements in power industry algorithms will improve power plant operation resulting in greater efficiency, improved grid dispatch, and reduced emissions, which will reduce operating costs. Specifically, this project will provide a means to dynamically monitor these data from existing and advanced sensors to correlate data into meaningful operating information that will allow for better control of transient conditions.
CFD Research Corporation **FE0005867**	Computational Capabilities for Predictions of Interactions at the Grain Boundary of Refractory Alloy	4	This project will accelerate development of new materials that can improve the efficiency of slagging gasification equipment. Improvement to high-temperature advanced materials will promote the development of advanced gasification designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will develop ReaxFF [reactive force field] potentials for predicting interactions of chromia/alumina-based refractories with sulfur, iron oxide (FeO), and aluminum oxide (Al_2O_3) and compare the properties against existing materials based on the molecular dynamic simulator to provide improved refractories for slagging gasifiers.
Energy Industries of Ohio, Inc. **FE0000234**	Steam Turbine Materials for Advanced Ultra-Supercritical Coal Power Plants	4	This project will examine steam turbine materials for A-USC coal power plants. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures. This will lead to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will evaluate promising materials to develop data necessary for the design of a steam turbine operable at A-USC conditions through research on the mechanical properties, oxidation resistance, weldability, and suitability of alloys and coatings.
Energy Industries of Ohio, Inc. **FG26-01NT41175**	Development of Advanced Materials for Ultra-Supercritical Boiler Systems	4	This project will facilitate development of advanced materials for ultra-supercritical (USC) boiler tubes. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures. This will lead to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will define and implement ways of producing improved alloys, fabrication processes, and coating methods that allow boilers to operate at high temperature and pressures; participate in the certification process of the ASME; and generate data to lay the groundwork for ASME code approved of alloys, where necessary.
General Electric Company **FE0005859**	Modeling Creep-Fatigue-Environment Interactions in Stream Turbine Rotor Materials for Advanced Ultra-Supercritical Power	4	This project will enable more accurate prediction of long service life of advanced alloys for A-USC power. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will develop and demonstrate computational algorithms for alloy property predictions, and will model key mechanisms that contribute to the damage caused by creep-fatigue-environment interactions.
Howard University **FE0011515**	Novel Low-Cost Environmentally Friendly Synthetic Approaches toward Core Shell Structured Microparticles for Fossil Energy Applications	2	This project will develop novel low-cost environmentally friendly synthetic approaches toward core shell structured microparticles for fossil energy applications. Improvement to advanced combustion technology will promote the development of advanced power plant designs that can lead to improvements in efficiency and operational flexibility and resulting lower capital and operating costs. Specifically, this project will synthesize and characterize Fe_2O_3-shell/Al_2O_3-core microparticles using the technique of cyclic reduction/oxidation of the iron component of the particle using modeling and testing to validate results.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Idaho National Laboratory **FWP-1168-100159**	Influence of Processing on Microstructure and Properties of Iron Aluminides and Coatings	3	This project will determine the influence of thermal spray processing parameters on the microstructure, stress state, and performance of advanced coatings for high-temperature environmental resistance in fossil energy applications. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will use in situ diagnostics associated with the application of coatings to relate thermal spray particle characteristics to the observed coating microstructure and residual stress state.
NETL-ORD **FWP-2012.03.01.2.1**	Task 2.1: Oxy-Combustion Environment Characterization—Fireside Corrision	3	This project focuses on evaluation of fireside corrosion and steam-side oxidation in oxy-combustion systems. Identification of alloys that can withstand the harsh physical and chemical conditions associated with oxy-combustion environments will lead to decreases in operating costs. Specifically, experiments will be conducted to elicit information as to the best oxy-fuel combustion designs, such as flue gas recycle sources and the use of staged combustion burners.
NETL-ORD **FWP-2012.03.01.2.2**	Task 2.2: Oxy-Combustion Environment Characterization—Steamside Oxidation	3	This project focuses on evaluation of fireside corrosion and steam-side oxidation in oxy-combustion systems. Identification of alloys that can withstand the harsh physical and chemical conditions associated with oxy-combustion environments will lead to decreases in operating costs. Specifically, experiments will be conducted to elicit information as to the best oxy-fuel combustion designs, such as flue gas recycle sources and the use of staged combustion burners.
NETL-ORD **FWP-2012.03.01.4.1**	Task 4.1: Alloy Manufacturing and Process Development—Large-Scale Ni-Based Alloys	5	The focus of this project is the development of alloys and processes that can practically be made at the scale of manufacturing deployment. The use of these alloys and processes will lead to reduced operating costs in USC and A-USC environments. Specifically, this project will include experimentation and computational studies on Ni-base alloys.
NETL-ORD **FWP-2012.03.01.4.3**	Task 4.3: Alloy Manufacturing and Process Development—Optimized Alloys for USC and A-USC Compnents	4	The focus of this project is the development of alloys and processes that can practically be made at the scale of manufacturing deployment. The use of these alloys and processes will lead to reduced operating costs in USC and A-USC environments. Specifically, this project will include experimentation and computational studies on Ni-base alloys.
NETL-ORD **FWP-2012.03.01.4.4**	Task 4.4: Large-Scale 9 Percent, Cr Steel Casting for USC 650 °C Boiler and Steam Turbine Components	3	The focus of this project is the development of a new nominal 9 wt % chrome content iron-based alloy with improved creep strength for steam turbine rotor applications. This project will include experimentation and computational work.
NETL-ORD **FWP-2012.04.01.5**	Innovative Process Technologies—Task 5: Computational Materials	3	This project will develop and validate computational atomistic simulations for key variables and parameters required for the microkinetic model to predict oxidation behavior of alloys. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating capital and operating costs. Specifically, this project will evaluate the influence of ambient gases (O_2, H_2, H_2O, and CO_2) to predict the influence on alloy surfaces.
North Carolina State University **FE0011247**	Rational Design of Mixed-Metal Oxides for Chemical Looping Combustion of Coal Via Computational Experimental Studies	2	This project will develop rational design of mixed-metal oxides for CLC of coal via computational experimental studies. Improvements to advanced combustion technology will promote the development of advanced power plant designs that can lead to improvements in efficiency and operational flexibility and result in lower capital and operating costs. Specifically, this project will develop a systematic approach to quantify the relationships among the compositional, structural, and reactive properties of the mixed-metal-oxide-based oxygen carriers used in chemical looping, which will lead to systematic and quantitative criteria for oxygen carrier development.
Oak Ridge National Laboratory **FWP-FEAA061**	Materials for Ultra-Supercritical Steam Power Plants	5	This project will develop the materials technology required to operate an ultra-supercritical steam boiler. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will evaluate the long-term behavior of candidate alloys, investigate the effects of processing variables, provide fundamental research in microstructural evolution at very long times using electron microscopy and computational thermodynamics, and provide data necessary to produce material models.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Oak Ridge National Laboratory **FWP-FEAA069**	Ultra-Supercritical Steam Cycle Turbine Materials	4	This research will provide critical support for the materials technology needed to design steam turbines capable of reliable operation at temperatures and pressures typical of A-USC steam conditions. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will provide independent materials assessment, testing, and development for evaluation and development of high-temperature Ni-based alloy castings for A-USC steam turbine casing including micro-characterization, development of constitutive equations or predictive models, and upgrading of the damage evaluation and life-prediction criteria.
Oak Ridge National Laboratory **FWP-FEAA105**	Bespoke Materials Surfaces	3	This project will identify coating materials and application techniques that have the potential to cost-effectively protect coal-fired boiler waterwall tubes in harsh, corrosive operating environments. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will develop a family of material coatings to address the requirements of coal-fired waterwall tube fireside protection, determine how surfaces and interfaces affect selected properties, and investigate how the desired combination of properties can be incorporated into a coating and a process for its deposition.
Oak Ridge National Laboratory **FWP-FEAA106**	Understanding Corrosion in Oxy-Fired Systems	3	This project will determine the temperature-dependent corrosion mechanisms of candidate high-temperature alloys and coatings in oxy-firing systems. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will use thermochemical modeling results to identify the typical and extreme values of the levels of various gases expected to influence high-temperature corrosion behavior of oxy-fired plants.
Oak Ridge National Laboratory **FWP-FEAA107**	Improving the Performance of Creep Strength-Enhanced Ferritic Steels	3	This project will address (1) controlling creep strength-enhanced ferritic (CSEF) steels' mechanical properties, microstructure, their dependence on chemical compositions heat treatments and (2) understanding the causes of type IV failure and developing strategies to minimize or eliminate it in these steels. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will rely on fundamental and applied studies of the effects of heat treatment, welding, and process control on microstructural evolution and material properties in CSEF steels.
Oak Ridge National Laboratory **FWP-FEAA109**	Qualification of New, Commercial ODS Alloys for Use in Advanced Fuel Processes	3	This project will determine the capabilities of new commercially produced oxide-dispersion-strengthened (ODS) alloys for application at high-temperatures in environments associated with advanced fossil combustion and conversion processes. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will produce rods and/or sheets from the alloy powders, characterizing their structure, oxidation resistance and mechanical properties, and comparing their measured properties with target specifications for high-temperature applications; analyze the feasibility of reducing the cost of ODS alloys by alternative powder alloying or consolidation methods; determine the microstructure and mechanical properties of friction stir welding ODS joints; and develop oxidation lifetime models in relevant environments.
Ohio State University Research Foundation **FE0008960**	Effective Exploration of New 760 °C Capability Steels for Coal Energy	3	The project will develop new steels capable of operating at A-USC conditions. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will use computational thermodynamics and high-throughput diffusion multiples experiments to focus on steel compositions with high iron and chromium concentrations for cost reduction, oxidation, and hot-corrosion resistance.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Pacific Northwest National Laboratory **FWP-12461**	Joining of Advanced High-Temperature Materials	3	This project will demonstrate joining of advanced high-temperature materials. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will prove that friction stir welding can be used to fuse materials and that the materials can withstand the environment within a USC boiler to enable cost-effective oxy-combustion systems through creep testing, microstructure characterization, and mechanical properties testing.
Pacific Northwest National Laboratory **FWP-60098**	Low-Cost Fabrication of ODS Materials	3	This project will examine the feasibility of low-cost fabrication of ODS materials. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will include adapting a high-shear, friction-based method of consolidating metal powders directly into round billets, rods, and tubes.
Purdue University **FE0011291**	Predicting Microstructure-Creep Resistance Correlation in High-Temperature Alloys Over Multiple Time Scales	2	This project will predict microstructure-creep-resistance correlation in high-temperature alloys over multiple time scales. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility, resulting in lower capital and operating costs. Specifically, this project will predict the creep and associated microstructure evolution of tungsten-based refractory alloys using grain boundary (GB) diagrams to establish time-dependent creep resistance and associated microstructure evolution of GBs/intergranular films (IGFs) controlled creep as a function of load, environment, and temperature.
Southern Illinois University **FE0008864**	HVOF [High-Velocity Oxy-Fuel] Thermal Spray TiC/TIB_2 Coatings of A-USC Boiler/Turbine Components for Enhanced Corrosion Protection	3	This project will develop HVOF thermal spray coatings for use on A-USC boiler and turbine components for enhanced corrosion protection. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and result in lower operating costs. Specifically, this project will develop (1) new coatings to improve corrosion resistance of boiler materials and (2) fireside corrosion protection of tubes and turbine blade materials, preparing the new coating by HVOF spray coating of titanium carbide (TiC) and titanium diboride (TiB_2) nanoparticles synthesized by a patented process.
Southern University and A&M College System **FE0011550**	An Integrated Study on a Novel High-Temperature High-Entropy Alloy	2	This project will develop a novel integrated method to improve and design the high-entropy alloys (HEAs) for high-temperature and high-pressure gas turbine application. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will perform molecular dynamics/Monte Carlo and interface energy HPC simulation on the HEA models to screen candidates for high-temperature and high-pressure, oxidation-resistant and low-temperature ductile ODS HEA and validate performance with experiments on the most promising materials.
Southern University System **FE0007220**	An Integrated Study of a Novel Thermal Barrier Coating for Niobium-Based High-Temperature Alloy	2	This project will focus on development of advanced thermal-based coatings (TBC) to improve the performance of coatings for niobium (Nb)-based, high-temperature alloys. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility. Specifically, this project will utilize advanced computer simulation to model the performance of numerous TBC formulations to identify the most promising candidates for testing.
Southern University System **FE0008382**	Novel Nanosize Oxide-Dispersion-Strengthened Steels Development Through Computational and Experimental Study	2	This project will focus on development of advanced ferritic-ODS alloy materials for use in advanced power systems. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility. Specifically, this project will use computational techniques to evaluate numerous formulations of alloys and examine their theoretical properties for enhanced performance consistent with the program goals, and the most promising alloys will be fabricated for testing to confirm the model's predictions.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
Tennessee State University **FE0003798**	Computational Studies of Physical Properties of Nb-Si Alloy	3	This project will focus on development of Nb-silicon (Si) alloys that will improve the high-temperature performance of advanced power-generation components. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility. Specifically, this project will evaluate the properties of numerous formulations of Nb-Si alloys with up to seven elements to identify materials that show the optimum properties for use as turbine components.
Tennessee State University **FE0011549**	Large-Scale Screening of Low-Cost Ferritic Steels Designs for Advanced Ultra-Supercritical Boiler Using First Principles Methods	2	This project will develop low-cost ferritic steels designed for high-temperature service. Improvements to high-temperature advanced-materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will use first principles methods to develop steels for further study.
Texas Engineering Experiment Station **FE0008719**	Synergistic Computational and Microstructural Design of Next-Generation High-Temperature Austenitic Steel	2	This project will develop synergistic computational and microstructural design of next-generation high-temperature austenitic steel. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will developing the next-generation advanced austenitic stainless steels that are capable of operating at the extreme conditions associated with advanced fossil energy power-generation plants by carefully designing microalloying technology.
Trustees of Dartmouth College **FE0008857**	Laves Phase-Strengthened Austenitic Steels for Coal-Fired Power Systems	2	This project will develop Laves phase-strengthened austenitic steels for coal-fired power systems. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and result in lower operating costs. Specifically, this project will investigate the strengthening mechanisms using models of both the precipitation kinetics and deformation behavior of aluminum-alloyed, Laves phase-strengthened austenitic steels, by assessing and documenting material behavior under a variety of conditions.
Trustees of Indiana University **FE0008868**	Novel Functional-Gradient Thermal Barrier Coatings in Coal-Fired Power Plant Turbines	3	This project will develop novel functional-gradient TBCs for coal-fired power plant turbines. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will develop a manufacturing process to produce novel low-thermal-conductivity and high-thermal-stability pyrochlore oxide-based double-layer coatings, which will improve high-temperature corrosion resistance and demonstrate lower thermal conductivity and better thermal stability.
University of Illinois **FE0011194**	Serration Behavior of High-Entropy Alloys	2	This project will lead to improved understanding of serration behavior of high-entropy alloys. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower capital and operating costs. Specifically, this project will study serration behaviors in HEAs under a wide range of strain rates, temperatures, and compositions, compression and tension behaviors to elucidate the underlying mechanisms of plastic deformation in HEAs using a model to predict fracture strength and creep life.
University of Missouri, Kansas City **FE0004007**	Ab Initio Modeling of Thermomechanical Properties of Mo-Based Alloys for Fossil Energy Conversion	3	This project will conduct ab initio modeling of thermomechanical properties of Mo-based alloys for fossil energy conversion. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will develop extensive computational modeling techniques for Mo-based composite alloys that can be used in a high-temperature, high-pressure environment for applications in fossil energy conversion technology.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
University of Missouri, Kansas City **FE0005865**	Large-Scale Simulations of the Mechanical Properties of Layered Transition Metal Ternary Compounds	3	This project will conduct large-scale simulations of the mechanical properties of layered transition metal ternary compounds. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating capital and operating costs. Specifically, this project will develop predictive modeling of a new class of materials to fulfill demanding applications in the next generation of fossil energy power systems and contribute in reducing development time to less than 5 years by modeling and performing laboratory testing of layered transition-metal carbides or nitrides.
University of North Texas **FE0008648**	Computational Microstructural Optimization Design Tool for High-Temperature Structural Materials	3	This project will develop a methodology for microstructural optimization of alloys for high-temperature structural materials. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will develop a new computationally designed Ni-Cr alloy using an integrated microstructural design approach for materials development.
University of Tennessee **FE0005868**	Computational Design of Creep-Resistant Alloys and Experimental Validation in Ferritic Superalloys	4	This project will develop a computational design of creep-resistant alloys and experimental validation in ferritic superalloys. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will investigate the creep properties of the proposed FBB8 alloy with titanium additions of 2 and 6 wt %, which should further improve creep resistance.
University of Tennessee **FE0008855**	Experimental and Computational Investigation of High-Entropy Alloys for Elevated High-Temperature Applications	3	This project will identify and develop HEAs that have the key mechanical properties for use at elevated temperatures. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and result in lower operating costs. Specifically, this project will utilize in situ testing of the mechanical behavior under uniaxial tension and compression or creep loading to identify deformation mechanisms under various stress loads at elevated temperatures.
University of Tennessee **FE0011585**	Developing Novel Multifunctional Materials for High-Efficiency Electrical Energy Storage	2	This project will develop novel multifunctional materials to improve the efficiency of energy storage technologies. Improvement to energy storage technology will promote improved utilization of power plant assets that can provide operational flexibility and result in lower capital and operating costs for energy supply. Specifically, this project will make much thinner and more controllable multifunctional materials with lower flow/interfacial resistance and higher thermal/electric conductivities, thus significantly improving efficiencies of the electrolyzer or other associated energy storage devices.
University of Texas at El Paso **FE0008400**	A Computational Experimental Study of the Plasma Processing of Carbides at High Temperatures	2	This project will develop a computational experimental study of plasma processing of carbides at high temperatures. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility resulting in lower operating costs. Specifically, this project will investigate the effects of the plasma flow dynamics within the carbide pores to impede oxygen ingress through the scale and will determine the effect of the gradient established by the electromagnetic field on mass transfer on pore surfaces as well as the kinetics within the pore wall.
University of Texas at El Paso **FE0008470**	Mechanically Activated Combustion Synthesis of $MoSi_2$-Based Composites	3	This project will develop mechanically activated combustion synthesis of $MoSi_2$-based composites. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will develop a novel and competitive processing route for manufacturing $MoSi_2$-based composites that are promising candidates for use as structural materials in advanced fossil-energy applications.

Table 16. **Crosscutting Research Composite Results**

Performer **Agreement Number**	Project Title	TRL	Relevancy Statement
University of Texas at El Paso **FE0008548**	Design Optimization of Liquid-Fueled High-Velocity Oxy-Fuel Thermal Spraying Technique for Durable Coatings for Fossil Power Systems	2	This project will design optimization of liquid-fueled HVOF thermal spraying technique for durable coatings for fossil power systems. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will develop a knowledge database of liquid-fueled HVOF thermal spraying technique processes and coatings developments so that durable coatings suitable for extreme environments of fossil-fueled power liquid-fueled HVOF process for a range of operating and systems can be developed.
University of Toledo **FE0008774**	Fabrication and Processing of Next-Generation Oxygen Carrier Materials for Chemical Looping Combustion	2	This project combines synthesis and processing protocols to produce and characterize laboratory-scale quantities of new oxygen carrier materials for CLC. Improvements to advanced combustion technology will promote the development of advanced power plant designs that can lead to improvements in efficiency and operational flexibility and result in lower capital and operating costs. Specifically, this project will perform thermogravimetric and differential thermal analysis (TG-DTA), abrasion and crush strength tests, and other analytical tests to determine the physical, structural, and chemical characteristics of a matrix of substituted perovskite compositions.
University of Washington **FE0007272**	High-Temperature Thermoelectric Oxides Engineered at Multiple Length Scales for Energy Harvesting	3	This project will explore a novel class of 'n' type thermoelectric oxides that are stable at high temperature in the coal-fired flue gas. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will use combinatorial materials exploration to rapidly screen a broad composition range to identify the most promising compositions of ferroelectric materials with high Curie temperatures, promising 'n' type thermoelectric oxides to make oriented crystalline oxides.
University of Wisconsin System **FE0007377**	Multiscale Computational Design and Synthesis of Protective Smart Coatings for Refractory Metal Alloys	3	This project will employ a new smart coating concept for refractory metal-borosilicide and -aluminide systems in order to provide a 200–400 °C increase in temperature resistance beyond that of current Ni-based superalloys in materials. Improvement to high-temperature advanced materials will promote the development of advanced power plant designs that can operate at higher temperatures and pressures, leading to improvements in efficiency and operational flexibility and resulting in lower operating costs. Specifically, this project will use empirical results from past work and computer modeling results to develop and test new refractory alloy coatings.
Key Technology—Environment and Innovative Energy Concepts			
NETL-ORD **FWP-2012.04.01.4**	Innovative Process Technologies—Task 4: Innovative Energy Concepts	3	The purpose of this activity is to complete the literature review on MHD power technology. The impact of this technology may be to identify opportunities to provide more electrical power output and greater efficiency for power generation, which could lower the operating cost for advanced power systems. Specifically, this project will examine DPE opportunities based on historical work performed on MHD.
University of Wyoming Research Corporation **FC26-08NT43293**	DOE-WRI [Western Research Institute] Cooperative Research and Development Program for Fossil Energy-Related Resources	5	This project focuses on developing, commercializing, and deploying technologies of value to assist industry with efficient, nonpolluting energy technologies and competitively meet requirements for clean fuels, chemical feedstocks, electricity, and water resources. The impact of this technology is to mitigate pollution from future gasification and combustion facilities by improving efficiency and improving environmental acceptability by reducing emissions and recovering water for power plant use thus lowering capital and operating costs. Specifically, this project provides joint research to create advanced sorbents for reduction of sulfur from syngas and combustion streams and to recover water for power plant use.

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CCS 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.

CCS DEMONSTRATIONS

OVERVIEW

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. Currently, there are 50 technologies in the CCS and Power Systems R&D program area that are being considered for large-scale testing.
- **PATHWAY NO. 2–EARLY FULL-SCALE COMMERCIAL DEMONSTRATIONS:** FE's CCS and Power Systems R&D program area develops individual technologies to the point of demonstration readiness. In general, this corresponds to TRL rating levels of 6 or 7. The CCS Demonstrations program area is 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 demonstration platforms typically consist of multiple technologies, some of which are developed under the CCS and Power Systems R&D umbrella, while others may have been developed by the recipients or their equipment suppliers. Accordingly, some of the technologies that constitute the entire demonstration platform may enter with a TRL 9 rating and are considered to be "enabling" technologies necessary to facilitate the demonstration of the lesser rated technologies. During the course of demonstration, it is possible for some of these TRL 9 technologies previously considered to be commercially ready to be shown to need additional R&D due to integration considerations. Currently, there are 14 technologies in the CCS and Power Systems R&D program area that are being considered for full-scale commercial demonstration.

As shown in Table 17, 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.

Table 17. **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**

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: Clean Coal Power Initiative (CCPI), FutureGen 2.0 (FG 2.0), and Industrial Carbon Capture and Storage (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). Figure 30 illustrates the relationship of these eight demonstration platforms to the four pathways and the three program components.

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. Table 18 distinguishes these technologies by platform.

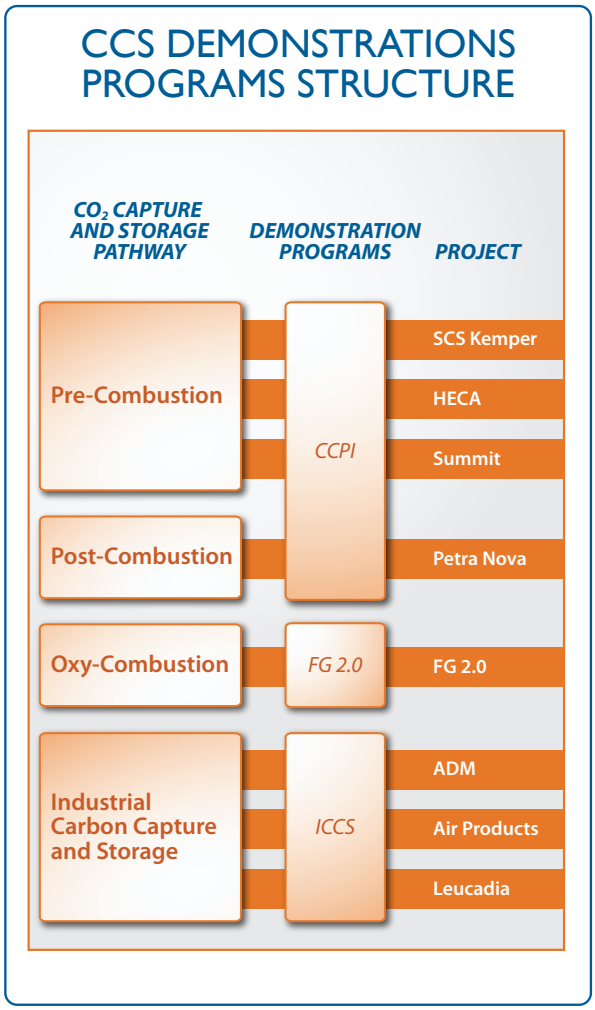


Figure 30. CCS Demonstrations Program Structure

Table 18. Active Demonstrations—Technology Characterizations

Platform	Technologies Requiring Further Validation	Proven Technologies
SCS-Kemper [Southern Company Services, Inc.]	• Coal dryer • Coal feeder • Advanced gasifier • Water-gas-shift reactor • Advanced gas turbine • Particulate collection • CO_2 capture process	• Coal mill • Heat recovery steam generator (HRSG) • Steam turbine • Syngas cooler • Sulfuric acid plant • Mercury removal • CO_2 drying/compression • CO_2 transport
HECA [Hydrogen Energy California, LLC]	• Coal/petcoke feeder • Advanced gasifier • Water-gas-shift reactor • Advanced gas turbine • Urea/ammonia nitrite plant • CO_2 capture process • MVA process	• Coal/petcoke mill • Air separation unit (ASU) • Steam turbine • HRSG • Steam condenser • Syngas cooler • Sulfur plant • Ammonia plant • Mercury removal • Particulate collection • CO_2 drying/compression • CO_2 transport
Summit [Summit Texas Clean Energy, LLC]	• Advanced gasifier • Water-gas-shift reactor • Advanced gas turbine • HRSG • Steam turbine • Steam condenser • Water treatment system • Urea production • CO_2 capture process • MVA process	• Coal mills • Coal feeders • ASU • Syngas cooler • Sulfuric acid plant • Mercury removal • Particulate collection • CO_2 drying/compression • CO_2 transport
Petra Nova Parish Holdings [formerly NRG Energy, Inc.]	• CO_2 capture process • MVA process	• Gas turbine • HRSG • CO_2 drying/compression • CO_2 transport
FutureGen 2.0	• Oxy-fired boiler • ASU • Sulfur removal • CO_2 compression and purification • MVA process • Carbon storage system	• CO_2 transport
ADM [Archer Daniels Midland Company]	• MVA process • Carbon storage system	• CO_2 drying/compression • CO_2 transport
APCI [Air Products and Chemicals, Inc.]	• Vacuum swing adsorption • MVA process	• Gas turbine • HRSG • CO_2 drying/compression • CO_2 transport
Leucadia [Leucadia Energy, LLC]	• MVA process	• CO_2 capture process • CO_2 drying/compression • CO_2 transport

More information on these active demonstrations and their configurations can be found by visiting the individual Major Demonstration project factsheets (click links below).[1]

SCS-KEMPER | HECA | SUMMIT | PETRA NOVA

FUTUREGEN 2.0 | ADM | APCI | 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.[2]

Figure 31 links the Technology Areas to the related development pathways through the CCS Demonstrations program and projects.

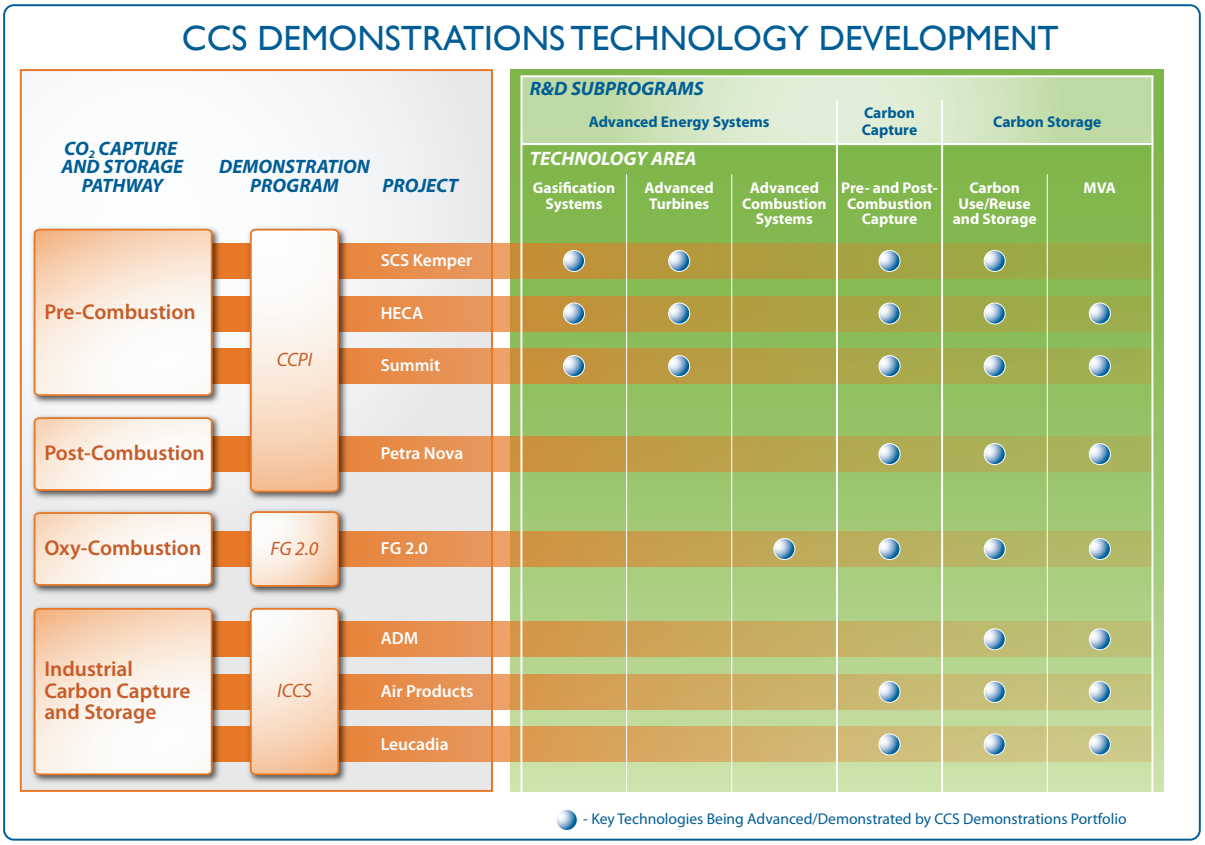


Figure 31. CCS Demonstrations Technology Development

1 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

2 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 19. A final TRA will be conducted following project completion as part of the PPA.

Table 19. 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 Strategic Center for Coal (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 the Department of Defense (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 Technology Readiness Levels (TRL), 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

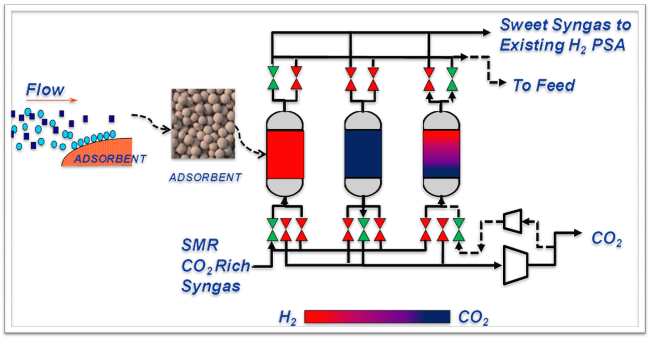
DOE selected Air Products and Chemicals, Inc., to receive ICCS program funding through the American Recovery and Reinvestment Act of 2009, for its project entitled, "Demonstration of CO_2 Capture and Sequestration of Steam Methane Reforming Process Gas Used for Large-Scale Hydrogen Production." For this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

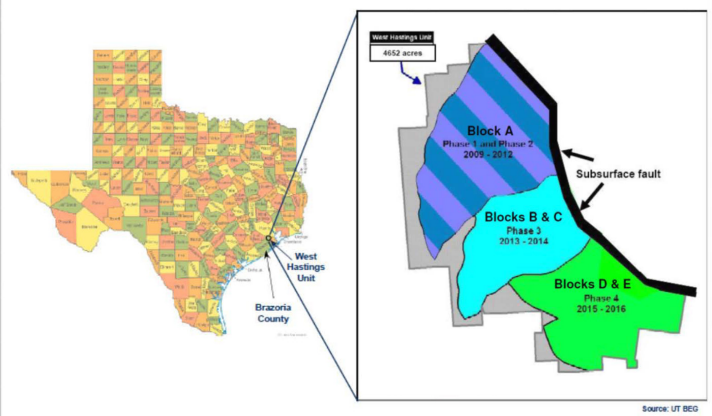
Air Products has retrofitted its two Port Arthur SMRs with a VSA system to separate the CO_2 from the process gas stream, followed by compression and drying processes. This process is designed to concentrate the initial stream containing from 10–20 percent CO_2 to greater than 97 percent CO_2 purity. 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.

Vacuum Swing Adsorption ("VSA") Process for CO_2 Separation





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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PARTNERS

Denbury Onshore, LLC

PROJECT DURATION

Start Date
11/16/2009

End Date
09/30/2015

U.S. DEPARTMENT OF ENERGY

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APPENDIX A—LIST OF ABBREVIATIONS

2-D	two-dimensional
3-D	three-dimensional
ABC	ammonium bicarbonate
AC	ammonium carbonate
ADM	Archer Daniels Midland Company
AEC	Anode-Electrolyte-Cathode
AIChE	American Institute of Chemical Engineers
Al_2O_3	aluminum oxide
ALAMO	Automated Learning of Algebraic Models for Optimization
APCI	Air Products and Chemicals, Inc.
ARRA	American Recovery and Reinvestment Act of 2009
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ASU	air separation unit
atm	atmosphere
Au	gold
A-USC	advanced ultra-supercritical
BDS	biocatalyst delivery system
BPM	Best Practice Manual
°C	degrees Celsius
CACHYS™	Capture of CO_2 by Hybrid Sorption Process
$CaCO_3$	calcium carbonate
CAPE	computer-aided process engineering
CARE	carbon absorber retrofit equipment
CBTL	coal and biomass to liquids
CCBTL	Coal and Coal-Biomass to Liquids
CCPI	Clean Coal Power Initiative
CCRP	Clean Coal Research Program
CCS	carbon capture and storage
CCSI	Carbon Capture Simulation Initiative
CDCL	coal-direct chemical looping
CFD	computational fluid dynamics
CH_4	methane
CLC	chemical looping combustion
CLG	chemical looping gasification
CMAS	calcium-magnesium aluminosilicate
Co	cobalt
CO_2	carbon dioxide
CO_2BOL	CO_2 binding organic liquid
COE	cost of electricity
Cr	chromium
CSEF	creep strength-enhanced ferritic
Cu	copper
CVP	crystal viscoplasticity
DIAL	differential absorption LIDAR
DNS	direct numerical simulation
DoD	Department of Defense
DOE	Department of Energy
DPE	direct power extraction
EASiTool	Enhanced Analytical Simulation Tool
EBC	environmental barrier coating
ECBM	enhanced coalbed methane
ECM	electrochemical membrane
EGR	exhaust gas recirculation
EOR	enhanced oil recovery
EPA	Environmental Protection Agency
EPAct	Energy Policy Act of 2005
°F	degrees Fahrenheit
FE	Office of Fossil Energy
Fe	iron
FeO	iron oxide
FG 2.0	FutureGen 2.0
FMS	frequency-modulation spectroscopy
FPM	Federal Project Manager
F-T	Fischer-Tropsch
FWP	field work proposal
FY	fiscal year
Ga_2O_3	gallium oxide
GB	grain boundary
GHG	greenhouse gas
GPRA	Government Performance and Results Act
GPS	gas pressurized stripping
GSRA	Geologic Storage Technologies and Simulation and Risk Assessment
GSSC	Geologic Sequestration Site Characterization
GSTR	Geologic Sequestration Training and Research
H_2	hydrogen
H_2O	water
H_2S	hydrogen sulfide
HEA	high-entropy alloy
HECA	Hydrogen Energy California, LLC
HES	high-efficiency system
HHC	high-hydrogen content
HMB	hybrid molten bed
HPC	high-performance computing
HRSG	heat recovery steam generator
HTC	hydrothermal carbonization
HTDP	high-temperature desulfurization process
HTM	hydrogen transport membrane
HVOF	high-velocity oxy-fuel

ICCS	Industrial Carbon Capture and Storage
IEA	International Energy Agency
IEC	innovative energy concept
IGCC	integrated gasification combined cycle
IGF	intergranular film
IGFC	integrated gasification fuel cell
IRL	Integration Readiness Level
ITM	ion transport membrane
kWe	kilowatt-electric
kWth	kilowatt-thermal
La	lanthanum
LES	large eddy simulation
Li	lithium
LIDAR	laser-induced differential absorption radar
LIF	laser-induced fluorescence
LSCF	lanthanum strontium cobalt ferrite
MCrAlY	chromium-aluminum-yttrium
MESA	merged environment for simulation and analysis
MFiX	Multiphase Flow with Interphase eXchanges
$MgCO_3$	magnesium carbonate
MHD	magnetohydrodynamics
Mo	molybdenum
MOF	metal organic framework
MRCSP	Midwest Regional Carbon Sequestration Partnership
MVA	monitoring, verification, accounting, and assessment
MW	megawatt
MWe	megawatt-electric
N_2	nitrogen
NAS	nonaqueous solvent
NASA	National Aeronautics and Space Administration
Nb	niobium
NCCC	National Carbon Capture Center
NDE	nondestructive evaluation
NETL	National Energy Technology Laboratory
Ni	nickel
NiAl	nickel aluminum
NO_x	nitrogen oxides
NRAP	National Risk Assessment Partnership
NSEMC	near-surface embedded microchannel
O_2	oxygen
ODS	oxide dispersion strengthened
OMB	Office of Management and Budget
ORD	Office of Research and Development
ORR	oxygen reduction reaction
OTM	oxygen transport membrane
oxy-PFBC	oxygen-fired pressurized fluidized-bed combustor
PBI	polybenzimidazole
PC	pulverized coal
PCOR	Plains CO_2 Reduction
Pd	palladium
PDMS	polydimethylsiloxane
PDU	process development unit
PEEK	polyether ether ketone
PF	perfluorocarbon
PIDAS	pressure-based inversion and data assimilation system
PPA	Post-Project Assessment
PSA	pressure swing adsorption
PSAR	polarity-swing-assisted regeneration
psi	pound per square inch
psia	pound per square inch absolute
PZ	piperazine
R&D	research and development
RCSP	Regional Carbon Sequestration Partnership
RD&D	research, development, and demonstration
ReaxFF	reactive force field
REI	Reaction Engineering International
RTI	Research Triangle Institute
RTSA	rapid temperature swing adsorption
RUA	Regional University Alliance
SBIR	Small Business Innovation Research
SCC	Strategic Center for Coal
scfd	standard cubic feet per day
scfm	standard cubic feet per minute
SCS	Southern Company Services, Inc.
SECA	Solid State Energy Conversion Alliance
SECARB	Southeast Regional Carbon Sequestration Partnership
Se	selenium
SeO_2	selenium dioxide
Si	silicon
SILM	supported ionic liquid membrane
SMR	steam methane reformer
SOFC	solid oxide fuel cell
SPPS	solution precursor plasma spray
Sr	strontium
SRL	Systems Readiness Level
TBC	thermal barrier coating
TCRP	trace contaminant removal process
TG-DTA	thermogravimetric and differential thermal analysis
TiB_2	titanium diboride
TiC	titanium carbide
TRA	Technology Readiness Assessment
TRIG™	Transport Reactor Integrated Gasification
TRL	Technology Readiness Level
TuRFR	turbine reacting flow rig

U	uranium
UQ	uncertainty quantification
USC	ultra-supercritical
UUV	unmanned undersea vehicle
VSA	vacuum swing adsorption
VUE	Visual User Environment
WO_3	tungsten trioxide
WRI	Western Research Institute
wt %	weight percent
Y	yttrium
YSZ	yttria-stabilized zirconia
ZnO	zinc oxide

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TECHNOLOGY READINESS ASSESSMENT
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